HAMILTON HARBOUR STUDY
1976

December 1978

Ministry
of the
Environment

Ontario

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Hamilton Harbour Study

1976

Water Resources Branch
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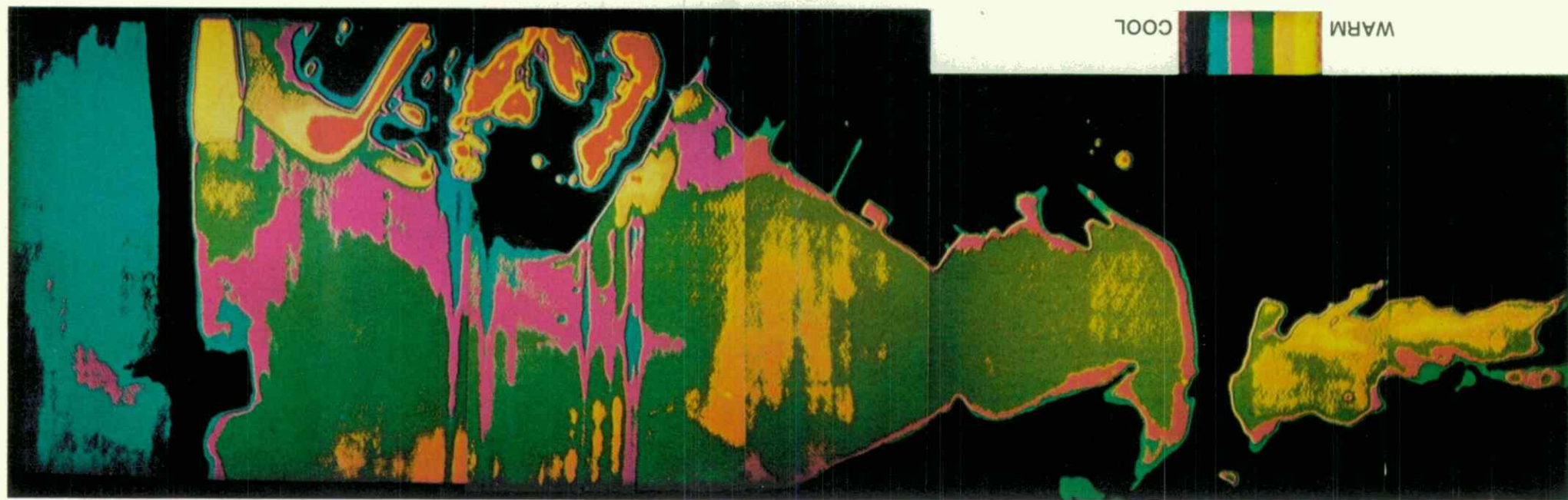
Frontispiece

A composite thermograph of Hamilton
Harbour from low level infra red
photographs taken on August 10, 1976.
This picture shows upwelling action on
the water directly above the diffuser
lines (refer to Figure I, Section A).
The cold water plume created by the
upwelling action moved away in a
south-east direction.

Hamilton Harbour Study

1976

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SUMMARY

This report summarizes the findings of physcial, chemical and
biological investigations carried out in Hamilton Harbour in 1976 by
the Ontario Ministry of the Environment and McMaster University.

The dissolved oxygen concentrations in the hypolimnium declined to
near zero early in the summer as in previous years. However, a
temporary recovery in the oxygen concentration occurred near the end
of July which coincided with peak aerator operations. Overall, the
artificial mixing system functioned below capacity and did not alter
the general pattern of dissolved oxygen change seen in previous
years. During May and June, the aerator lines were relocated to
avoid interruptions previously encountered from shipping traffic,
and operations did not begin until the middle of June.

In order to assess the oxygen conditions in Hamilton Harbour, field
and laboratory studies of oxygen concentrations, sediment oxygen
demand and water-column oxygen demand were carried out. It was
discovered that approximately 80% of the total oxygen demand is
associated with the water column and the remaining 20% is associated
with the sediments. The major source of oxygen to the harbour is
via atmospheric aeration (64 to 84%), with Lake Harbour exchange
(19%), photosynthesis (9-13%) and basin drainage (1%) comprising the
rest.

Nitrogen response to artificial mixing was difficult to assess
because of high ammonia loadings to the basin. Ammonia, nitrate and
total Kjeldahl nitrogen showed similar trends and concentrations to
previous years. However, nitrite did not show any of the large
accumulations which were evident in 1975.

Filtered reactive phosphorous (FRP) and total phosphorous (TP)
displayed seasonal and spatial patterns similar to those observed in
1975, with higher FRP values being associated with the shallow
stations.

Silica concentrations showed spring and fall maxima at all stations
except 258 which had a summer maximum. These trends were correlated
with the diatom crops in the harbour.

In 1976 copper and manganese concentrations were measured only from
September through November, since previous studies showed them to be
present in very low concentrations over the spring and summer. Zinc
and iron levels, which were intensively monitored, were found to be
present in excess of the IJC guidelines.

Conductivity and pH showed small but measurable declines over the
sampling season which were unrelated to aerator operations. Redox
potential measurements showed rapid changes during the period of
peak aerator operations, but these changes were more likely due to
lake-harbour exchanges.

The moderate turbidity levels of the harbour were found to be linearly related to the suspended solids which showed an abundance of particles of less than 2 mm. in diameter. Filtered organic carbon was found to comprise 70 to 80% of the total organic carbon. The filtered fraction is thought to be composed of a mixture of small particles, colloides and soluble materials. It was speculated that efficient artificial mixing could help in the stabilization of this component.

Analysis of sediment cores revealed that the harbour sediments are most severely polluted with zinc, lead and chromium compared with other Great Lakes' areas. The sediments contain lesser amounts of cadmium and mercury. The spatial distributions of these pollutants were similar to previous years, with the highest concentrations occurring in the deep water portions and in those areas adjacent to outfalls. Sulfide concentrations in the sediments were far lower in 1976 than in 1975 which is thought to be a result of incresed concentrations of sulfur oxidizing bacteria.

The fecal coliform organisims showed a decrease at all stations during 1976. The levels observed were generally below the 100 counts per 100 ml. requirement for body contact recreation. All taxa monitored, with the exception of the sulfur oxidizers, decreased in numbers in comparison to the 1975 data. A dramatic increase in population density of the sufur oxidizers was noted and probably resulted from improved oxygen availability due to artificial mixing and natural processes.

Chlorophyll a levels remained high, but still did not reflect the hypereutrophic state of the harbour as indicated by its high nutrient concentrations. Cryptomonads and flagellated greens compose significant portions of the phytoplankton populations of the harbour. These species commonly occur in areas with high organic loadings and are thought to be facultative heterotrophs which utilize organic carbon. Primary productivity, standing crop and community structure in the harbour appeared to be controlled more by physical processes rather than by nutrients.

An independent report entitled "The Biological Survey of Hamilton Harbour 1976" by B.B. Piccinin is available from the biology department, McMaster University, Hamilton, Ontario. It relates the physical and chemical environment with the primary productivity observed in the harbour. The report further describes the phytoplankton and zooplankton communities present. The McMaster report complements the information presented below.

This report consists of eight technical sections as follows:

A) Artificial Mixing
B) Oxygen Budget
C) Water Quality Update
D) Sediment Chemistry
E) Phytoplankton and Bacteria
F) Mass Exchange Between Hamilton Harbour and Lake Ontario
G) Physical Processes
H) Rates of Oxygen Utilization in the Hypolimnium

RECOMMENDATIONS

The aerator system must be fully operational by mid-May in order to accomodate the stored oxygen demands and prevent summer hypolimnetic anoxia. The system must deliver the required 0.140 $m^3 s^{-1}$ throughout spring and summer if hypolimnetic anoxia is to be prevented. The COD loadings to the harbour must be reduced as they represent a stored oxygen demand over the winter. The sources of heavy metals particularly zinc should be located and reduced.

DESCRIPTION OF HARBOUR

Hamilton Harbour is an enclosed body of fresh water at the western end of Lake Ontario, approximately 8 km in the east-west direction and 5 km in the north-south direction. It is connected to Lake Ontario by a ship's canal, 730 m long x 107 m wide and 10 m deep. The harbour contains approximatly $2.8 \times 10^8 m^3$ of water with a mean depth of 13 m. Hamilton Harbour receives drainage from a watershed of 500 km^2 through several small creeks which drain into the harbour with a total annual flow of $1.27 \times 10^8 m^3$; consequently, the natural throughput is approximately 45% per year.

The industries located on the highly developed south shore extract 26 $m^3 s^{-1}$ of harbour water as an industrial supply, returning a similar amount of effluent to the harbour. They also depend upon the harbour for shipping of raw materials and finished products.

Municipal utilities also use the harbour as receiving water for 10.2 $m^3 s^{-1}$ of treated wastes and for untreated storm sewer overflows estimated at 0.1 $m^3 s^{-1}$ during overflow periods. Together with the natural flow, sewage and stormwater effluent discharges result in a total annual flow of $4.5 \times 10^8 m^3$, or a throughput of approximatly 160% per year. Presently, the harbour is also used for recreational boating.

A. ARTIFICIAL MIXING

The artificial mixing system used in 1976 was the same design as that used in 1975. However, the aerator lines were relocated to extend northward from the north face of the Stelco dock to reduce damage due to shipping traffic. System operations did not begin until mid-June, when the bottom waters of the harbour were already approaching anoxia. Air flow did not attain maximum output until late July. Average flow rates were then reduced due to line problems and system failures.

Vertical thermal structures in the harbour could not be directly related to the mixing system because the harbour has a naturally variable thermal structure due to physical processes. The oxygen profiles were the most encouraging results from the mixing experiment. Relief of bottom anoxia was noted at the end of July and the beginning of August during periods of peak air flows.

Levels of FRP and TP remained high but varying from 2 - 48 mg/L and 0.38 - 118 mg/L respectively. They were unrelated to aerator activity. Ammonia, nitrate and total Kjeldahl nitrogen showed similar trends to previous years which were not related to the artificial mixing. Although, nitrite did not show any of the large accumulations which occurred in 1975. Silica concentrations and seasonal patterns were similar to those observed in previous years except for the summer peak at station 258 which was thought to be responsible for the maintenance of the summer diatom population. The vertical distribution of silica was more homogeneous in 1976 which was probably an effect of increased vertical turbulence as a result of the artificial mixing system.

Conductivity, pH, turbidity, suspended solids, total organic carbon and heavy metal concentrations showed similar patterns to those of 1975 and were unrelated to the operation of the artificial mixing device.

The bacterial community showed declines in the population densities of the coliforms, sulfur reducers and heterotrophs. Little or no change was seen in the Nitrosomonas densities. The numbers of sulfur reducing bacteria increased dramatically and coincided with a large decrease in the sediment sulfide contents. These changes are possibly a result of aerator activity.

The chlorophyll a concentrations remained high at 20 - 30 μg/L. Large vertical variations over the course of the sampling program were observed but were not directly related to the artificial mixing program. The species of phytoplankton found in the harbour were similar to those of 1975. The cryptomonads and flagellate greens, which are thought to be facultative heterotrophs, were constant community members. Summer peaks of Fragilaria crotonensis and Cyclotella menighiniana were present. The growth of these diatom species during the summer period which is normally dominated by green algae, is likely a result of both the higher silica concentrations seen at station 258 during this period and a vertically more turbulent environment as compared to this time period in 1975. It is felt that this vertically unstable and rapidly fluctuating environment not only limits total primary production but also controls the phytoplankton community composition. This latter point is demonstrated by the complete absence of blue-green algae.

B. OXYGEN BUDGET

In 1976 a series of field and laboratory studies were conducted to obtain a comprehensive oxygen budget for the harbour. To assess the relative importance of the individual processes, the harbour oxygen budget was estimated for three periods during the year. Spring (April 23 - June 19), when rapid decreases in oxygen stock took place, summer (June 20 - September 3), when conditions were nearly steady, and autumn (September 4 - October 27), when the oxygen stock slowly decreased, were the major periods identified in this study.

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The water column oxygen demand represents approximately 80% of the total oxygen demand. The remaining 20% of the oxygen demand is exerted by the sediments. Both the water column oxygen demand (WCOD) and the sediment oxygen demand (SOD) were found to increase with increasing concentrations of ambient dissolved oxygen in a linear fashion.

The chemical oxygen demand (COD) in the water column was quite constant throughout the year at 20 mg/L. The COD also showed little spatial variation either vertically or horizontally. In contrast, the biochemical oxygen demand (BOD_5) exhibited considerable variation in time and space. It was particularly high in the hypolimnium during the spring.

The oxygen sources to the harbour are atmospheric aeration, lake-harbour water exchange, net photosynthesis and basin drainage. Atmospheric aeration was found to be the most important process in supplying oxygen. Its contribution, as estimated from the total oxygen balance, ranges from 68 - 84% of the total oxygen supplied. This process of gas exchange between the atmosphere and water is aided by the natural instability of the water column which increases the diffusion of oxygen into the total water mass. It is felt that this natural instability was further enhanced by the operation of the artificial mixing device. Of the remaining processes, it is estimated that net photosynthesis contributes 7 - 19%, lake-harbour water exchanges through the ship canal contribute 6 -19% and basin drainage contributes less than 1% to the total oxygen supplied.

The total oxygen stock of the harbour was rapidly depleted in the late spring and showed partial recovery during the summer, perhaps as a result of sustained aerator operations. The stock was further, but more slowly, reduced during the autumn prior to isothermal conditions. To prevent this rapid and continued oxygen depletion, vertical transfer must be enhanced by more efficient aeration. Decreases in the BOD and COD loadings to the harbour would also decrease the water column oxygen demand which is the major sink of oxygen in the harbour.

C. WATER QUALITY UPDATE

The water quality survey program which was established in 1975, was continued in 1976. It was found, that the seasonal and depth variation of total Kjeldahl nitrogen (TKN), ammonia-N, nitrite-N and nitrate-N were similar to those observed in 1975. The maximum mean epilimnetic nitrite concentration was much lower than was observed in 1975 and in general eplimnetic concentrations were below 0.2 mg/L.

The depth-time distributions of both TP and FRP again showed no significant trends. The average values of 0.06 mg/L TP and 0.01 mg/L FRP are comparable to those concentrations observed in previous years.

The average surface molar N/P ratio (TKN/TP) of Hamilton Harbour, which was approximately 150, is roughly three times that of Lake Ontario and ten times that observed in algae. Therefore, the harbour is greatly enriched with nitrogen compared to Lake Ontario and algae.

The harbour-wide means of dissolved reactive silica (as Si) were far lower in 1976 than were observed in 1975. The normal pattern of lower epilimnetic concentrations, as compared with the hypolimnetic concentrations, disappeared in mid-summer and silica became vertically homogeneous presumably helped by artificial mixing.

The harbour-wide monthly means of zinc and iron showed no consistent spatial and depth variations and only irregular seasonal variations. Iron values, which were approximately 0.3 mg/L showed irregular seasonal variations, but zinc values showed a seasonal dependence with a summer maximum of 0.10 - 0.14 mg/L as compared with concentrations of less than 0.10 mg/L at other times. Copper values were found to be less than the detection limit of 0.01 mg/L and manganese values were generally below 0.08 mg/L. The average concentrations of iron and zinc were respectively at or in excess of the IJC water quality objectives.

D. SEDIMENT CHEMISTRY

Since events occurring at the sediment water interface play a strong role in regulating aqueous heavy metal and nutrient concentrations, further analysis of the sediment chemistry was conducted in 1976. On the basis of the 1975 results, a series of sediment core samples were collected in June and sectioned into top, middle and bottom portions. In addition to the four principle water chemistry stations, additional samples were collected from areas near the industrial shore line. Fewer locations were sampled (as compared with 1975) in the central deep zone of the harbour. Enrichment factors were calculated for each core and a factor analysis of similarity coefficients obtained by the ratio matching method was performed.

Hamilton Harbour sediments were most severly polluted with zinc, lead and chromium and to a lesser extent, with cadmium and mercury as compared with other Great Lakes' areas. The spatial distributions of these parameters were similar to previous years with the highest concentrations occurring in deeper zones and in areas adjacent to outfalls.

Sulfide concentrations were found to be lower in 1976 than in 1975. This is thought to be a result of the larger densities of sulfur oxidizers whose growth was stimulated by increased oxygen availability due to the operation of the artificial mixing system.

Factor analysis of the sample results revealed a more complex pattern than that observed in 1975. The analysis showed two major groupings for the deep water areas and other groupings for the shallowest areas, as well as a separate area which is most affected by lake-harbour exchange.

Data from both the 1975 and the 1976 studies have shown that the control of phosphorous release from the harbour sediments is much more complex than the simple iron-phosphorous-dissolved oxygen pattern reported in other studies. There existed a strong relationship between total phosphorous and total Kjeldahl nitrogen

in the surface portions of the cores. Phosphorous showed further
relationships with both cadmium and chromium. In view of this, it
was proposed that sediment samples be further analysed by a chemical
fractionation scheme to investigate the heavy metal-phosphorous
relationships. The chemistry of the sediment-water interface should
be investigated further by analysing water samples from just above
the interface.

E.   PHYTOPLANKTON AND BACTERIA

In 1976 phytoplankton were monitored at each metre depth at station
258. In addition, coincident light and temperature measurements
were taken. Major modifications in composition were noted as
compared with 1975, although the general associations of population
types with thermal regimes were the same. Periods of homogeneous
mixing were always dominated by diatoms. These species gave way to
a collection of cryptophytes at the end of April when the waters
were rapidly warmed and weak stratifications formed. These species
are thought to be facultative heterotrophs and can be found to a
greater or lesser extent at all times in the harbour.

The rapid attenuation of photosynthetic light in the harbour
resulted in a euphotic zone depth of about 4 m. It was this shallow
euphotic zone depth combined with a highly variable mixing zone
depth which resulted in the rapid shifts in species composition and
relatively low productivity in the harbour. The potential
production, as would be predicted on the basis of nutient
concentrations, was not reached throughout most of the year in the
harbour. The maximum assimilative potential was only realized
during the early summer when high temperatures coexisted with
sufficient oxygen concentrations. This period of longer day length,
greater light intensities and a relatively stable mixing depth was
dominated by a number of coccoid greens. The rapid flucuations in
mixing depths seen in the harbour in 1976 during this period
resulted in frequent rapid shifts in the species composition. The
physical regime was further reflected in the sustained summer diatom
population.

Bacteria samples were collected from April to November at the four
major sampling stations. Taxa monitored were selected as being
representative of the health aspects of water quality (fecal
coliforms), the oxidative state of the water column (sulfur
oxidizers, sulfur reducers, and Nitrosomonas), and the organic waste
assimilation potential of the harbour (heterotrophs).

Population densities showed a general decline for all species
monitored except for the sulfur oxidizers which showed large
increases in their numbers. These populations are dependent upon
the rare event of the coexistence of sulfide and oxygen. Therefore,
the increased densities of the sulfur oxidizing bacteria suggests
added vertical mixing as a result of the artificial mixing system.
All taxa except the sulfur oxidizers showed a general decline in
numbers with depth. The sulfur oxidizers however, increased with
depth, depending also upon the availabilty of reduced sulfur
compounds. The sulfur reducers and Nitrosomonas did not show any

definite seasonal trends. The heterotrophs were present generally in excess of 10^5 counts per 100 ml and showed a summer maximum. The sulfur oxidizers had densities in excess of 10^6 counts per 100 ml and also showed a summer maximum which declined during isothermal mixing conditions. Both the heterotrophs and the sulfur oxidizers combined to form a major component of the oxygen demand of the harbour. The fecal coliforms again were present in concentrations lower than those prior to 1975 and were generally less than 100 counts per 100 ml. Therefore, with regard to health criteria, the harbour would appear to be approaching a state where contact recreation could be permitted. However, a more intensive sampling routine would be required to more fully evaluate this aspect.

F. MASS EXCHANGE

Current meter data were collected from September 1 - 13 during 1975 at two levels on a single tower in the Burlington Ship Canal. It was estimated an average of $2.14 \times 10^6 m^3$ per day of harbour water flowed into the lake while $0.77 \times 10^6 m^3$ per day of lake water flowed towards the harbour. Therefore, there was a net exchange of water towards the lake. The harbour dilution factor was estimated at 0.0019 per day. These calculations were based on the excursion-episode method which excludes water movements which do not clear the confines of the channel.

Mass exchange through the ship canal is a complex process. It is important for maintaining and perhaps even improving the existing water quality in the harbour.

G. PHYSICAL PROCESSES

Physical processes in the harbour and the Burlington Canal were studied from 1972 to 1975 by operating a number of current meter networks.

Mass exchange of water occurs through the Burlington Canal which results in a net replacement of 1% of the harbour volume per day by lake water. Large currents of up to 144 cm s^{-1} were recorded in the canal. When average current speeds are used to compute water movements, they show a mass exchange of two to three times larger than the results obtained by the excursion-episode method.

Kenetic energy spectra computed from the mid-harbour locations are similar to those of the nearshore areas of Lake Ontario. In addition to demonstrating the lower five modes of the current periodicities of Lake Ontario, shorter periods were observed which reflect the local harbour geometry.

H. RATES OF OXYGEN UTILIZATION IN THE HYPOLIMNIUM

The rates of oxygen depletion due to water column processes were determined by McMaster Universtiy, using methods similar to the dark bottle portion of the Winkler method for measuring primary production. In addition, radioactive methane was used as a tracer to measure methane oxidation.

The average volumetric rate of oxygen consumption was 1 mg/L per day for the hypolimnium for the period of July 1 to August 5, 1976. Methane oxidation rates were generally an order of magnitude lower due to low methane concentrations. Also, sediment oxygen demand was estimated to be about 2 gm^{-2}.

These results suggest that water column processes, rather than sediment oxygen demands, dominate the rate of hypolimnetic oxygen depletion.

HAMILTON HARBOUR STUDY 1976

SECTION A

ARTIFICIAL MIXING

SUMMARY

The artificial mixing system used in 1976 was the same design as
that used in 1975. However, the aerator lines were relocated to
extend from the north face of the Stelco dock to avoid damage due to
shipping traffic. System operations did not begin until mid-June,
when the bottom waters of the harbour were already approaching
anoxia. Air flow did not attain maximum output until late July.
Average flow rates were then reduced due to line problems and system
failures.

Vertical thermal structures in the harbour could not be directly
related to the mixing system because the harbour has a naturally
variable thermal structure due to physical processes. Relief of
bottom anoxia was noted at the end of July and the beginning of
August during peak air flows.

Levels of FRP and TP remained high, ranging from 2 - 48 mg/L and
0.38 - 118 mg/L respectively, and were unrelated to aerator
activity. Ammonia, nitrate and total Kjeldahl nitrogen showed
similar trends to previous years which were not related to the
artificial mixing. However, nitrite did not show any of the large
accumulations which occurred in 1975. Silica concentrations and
seasonal patterns were similar to those observed in previous years
except for the summer peak at station 258 which was thought to be
responsible for the maintenance of the summer diatom population.
The vertical distribution of silica was more homogeneous in 1976
which was probably an effect of increased vertical turbulence as a
result of the artificial mixing system.

Conductivity, pH, turbidity, suspended solids, total organic carbon
and heavy metal concentration showed similar patterns to those of
1975 and were unrelated to the operation of the artificial mixing
device.

ARTIFICIAL MIXING REPORT 1976 FOR HAMILTON HARBOUR

INTRODUCTION

Since 1972, water quality studies of Hamilton Harbour have indicated that artificial mixing of the harbour waters is essential. Water quality had deteriorated to the extent that dissolved oxygen declined rapidly in the late spring, and seriously stressed the biological capacity of the harbour to stabilize the effluents of the cities of Hamilton and Burlington including their respective industries. This problem was compounded by high levels of zinc which were approaching acute toxicity levels and elevated levels of ammonia which were common in the spring period. The aesthetic qualities of the harbour waters were hindered by poor light penetration, with dissolved organics and small particulate materials limiting light penetration and giving the waters a "gray" colouring.

An initial trial of artificial mixing was attempted in 1975. During this time, excluding the last two weeks of July, mixing was insufficient as a result of mechanical failures. The effects of this trial run were encouraging, however, as dissolved oxygen increased, ammonia levels declined, and there was a vertical expansion of the zooplankton habitat. It was noted that flows of over 0.140 m^3/s (300 cfm) were required to have notable beneficial effects from artificial mixing.

The history of artificial mixing has been previously reviewed (M.O.E., 1974) but the application of mixing (to increase the waste assimilation capacity) of a large eutrophic body of water such as Hamilton Harbour was a new approach. Theoretical expectations were:

1. Limited phytoplankton standing crops by altering composition to diatoms which could be silica limited.

2. Lower chlorophyll a levels by redistribution of organisms.

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3. Improved light penetration by stimulating the production of
    heterotrophic bacteria to stabilize the filtered organic carbon
    components.

4. Decline in ammonia levels by providing an oxic environment to
    encourage nitrification.

5. Stabilize hydrogen sulphide by encouraging sulphur oxidizers.

6. Increase zooplankton habitat, provide food source for fish
    population.

7. Prevent resuspension of nutrients and metals from the sediments
    by providing an oxic microzone, and thus lowering the risk of
    metal toxicity problems.

Unlike many other mixing trials, the harbour receives high loadings
of nutrients, thus changes in the nutrient cycle will probably not
alter nutrient responses by the biota although nutrient utilization
will be decreased. The oxic environment might decrease dissolved
metal content in the water, although it is not known if total metal
concentrations would be altered.

THE MIXING SYSTEM

The mixing system was similar in design to the technique used in
1975. Polyethylene tubing with an internal diameter of 5.08 cm and
a pressure rating of 552 K Pa was attached to a 0.28 m^3/
compressor. Slit arrangement was identical to the 1975 system,
although larger slits (0.40 mm) were used to maintain higher flow
rates at lower pressures. This alteration was based on operational
problems the previous year, when sufficient flows were not possible
because of pressure limitations.

Continuous operations was not possible in 1975 as the diffuser lines crossed the shipping channel and were frequently damaged by anchors and by water currents created by larger vessels. To ameliorate this problem, the diffuser lines were run from the north wall of Stelco docks and crossed the shipping lines in much deeper waters. This relocation was successful, and continuous operation was achieved. The position of the four lines can be determined in Figure 1.

Operational schedules are summarized in Figure 2. From the middle of June to the first week of July, all four lines were placed and were operating. Line #4 initially presented some problems with separations, and was not functioning properly until August.

During the 1975 mixing experiment it was noted that flows of 0.14 m^3/s were required to have an effect on the vertical thermal structure of the harbour. Reasons for this critical flow have been outlined by Baines (1961). Large discharges of air result in heterogeneous mixtures of bubbles which are contained in a cone with an included angle of 12°. Water movement is induced by the rising bubbles, and the force exerted by a bubble on the water is proportional to its bouyancy. Water surrounding the bubble column is set into motion because of viscosity and lateral turbulence fluctuations. The ratio of water moved to air discharged has been characterized as;[1]

$$\frac{\text{Water Flow}}{\text{Air Flow}} = \frac{\text{Depth}^{0.66}}{\text{Air Flow}^{0.33}} \, f(1)$$

where f(1) is dependent on temperature and turbulence generated by the rising bubbles. Actual aeration directly from the bubbles is minimal (Pasveer, 1965) when compared to enhanced natural aeration caused by vertical mixing. Measurement of oxygen concentrations in the bubbles upon reaching the surface were made by Professor W. Snodgrass of McMaster University in 1976 who confirmed that the bubbles themselves were not a substantial source of oxygen to relieve dissolved oxygen stresses of the harbour.

Infrared photography was utilized to substantiate that artificial mixing was having a harbour-wide effect. On August 10, 1976 a low level colour infrared study revealed the action of lines on the water surface directly above the diffusers (frontispiece). This was followed by a more intensive thermal scan on the early morning of August 20. This scan of the harbour indicated cold upwellings ($17^{o}C$) over the diffuser section. These upwellings created a cold water plume which moved in a southeast direction across the length of the harbour. This cool temperature plume represents the surface area of the harbour where natural re-aeration has been stimulated by the mixing system.

These upwellings created a cold water plume which moved in a southeast direction across the length of the harbour. This cool temperature plume represents the surface area of the harbour where natural re-aeration has been stimulated by the mixing system.

Also of interest was the visual confirmation of exchange of harbour and lake water through the Burlington Ship Canal with a massive innoculation of Lake Ontario water (black plume $12^{o}C$) and evidence of warm Hamilton Harbour waters flowing into Lake Ontario. This photography confirms the harbour-wide effects of the mixing project. Apparently, the coldest water is found near boils, as large bubbles create the largest amount of turbulence bringing the cold anoxic bottom waters to the surface. The behaviour of the function f(1) would be erratic in this circumstance of density layers, thus the entrainment effects of rising bubbles are highly variable.

As in 1975, the 1976 installation was a month too late. By the middle of June the harbour waters had become low in dissolved oxygen and were approaching anoxia. This situation should be avoided as the aerator then has to satisfy oxygen demands such as COD, BOD, sediment oxygen demands and water column demands plus restore 1.5×10^{6} kg of oxygen to the basin. From the middle of July air flows from the aerator were over the critical 0.14 m^{3}/sec. Before this

date, circulation was not sufficient to satisfy the instanteneous oxygen demand of the harbour. To avoid a large oxygen deficit, artificial mixing must be initiated by the middle of May or sooner. From this time onward the water column has warmed sufficiently such that natural vertical mixing is suppressed, and the oxygen demands of the lower water exceed the vertical transfer of oxygen from the aerated surface waters.

A secondary mixing technique was investigated during the course of 1976. Professor M. Baird of McMaster University was engaged to determine the possibilities of using a vortex generator as a mechanism of vertical transfer of oxygen and for creating sufficient perturbations within the thermal barriers to invoke mass transfer between the upper and lower waters. The vortex generator consisted in part of an open ended cylinder inverted into the water. Pulses of air at time intervals (usually 20 seconds) were fed into the chamber, and donut shaped vorticies of water were generated. These vorticies would travel to or near the bottom of the harbour and disperse. Although only operated for small time periods (48 hours) the initial observation indicated the vortex generator could be useful in aerating particular trouble spots, or be used to increase the rate of stabilization of the sediments by forcing oxygenated water into them.

Temperature - Dissolved Oxygen

As noted in Figure 4 there was a definite surface cooling as a result of artificial mixing. This phenomenon was also noted in a separate study by McMaster University (Piccinin, 1977), where average surface temperatures declined 3 to $4^{o}C$ but were not directly separated as effects of mixing or atmospheric cooling. Temperatures near the upwellings were $17^{o}C$ and the surrounding waters ranged from $18^{o}C-22^{o}C$. Near the western end of the harbour and near outfall areas temperatures were in excess of $22^{o}C$.

Actual changes in vertical thermal structure could not be directly
related to the mixing system because the harbour has a natural
diffuse thermal gradient as a result of physical coastal processes.
This was more apparent in 1976 than 1975 as the average water column
temperatures were lower (Piccinin, 1977).

Vertical temperature profiles were obtained by using thermistors and
a bathythermocast. These frequently revealed the large influxes of
Lake Ontario water, but these masses were more easily defined with
oxygen profiles. Classical thermocline conditions of $1^{\circ}C$ change
of temperature per meter depth were not frequently observed except
during the incipient stages of autumn turnover when surface cooling
resulted in more distinct thermal profiles (Figure 3).

Mixing failed to increase the heat budget of the harbour and did not
stimulate sufficient vertical movement to obtain temperature
homogeniety with depth.

Oxygen profiles were by far the most positive aspect of the mixing
experiment. Vertical profiles revealed constant conditions of under
saturation in the epilimnion indicating that vertical transfer of
oxygen was occurring. This under saturation of oxygen in the upper
waters was a condition of the harbour without induced mixing because
of the weak stratification and discharges to the epilimnion.
Air-lifting of the water would enhance this vertical flux, and
result in increased aeration and higher oxygen stocks.

Many of the summer oxygen profiles (Figure 4) demonstrated oxygen
lenses in the lower waters. These lenses of oxygenated water were
mostly derived from mass exchange of lake and harbour water through
the Burlington Ship Canal. The cold lake water sinks to the
appropriate density layer and mixes across the harbour. The effects
of the lake water intrusions were not noted at stations 252 and 270
as a result of colder lake water tending toward lower depths with
densities similar to its own. This lens of oxygenated water would
not be a flat two-dimensional phenomenon but would tend to curve

upward as mixing would warm the water mass making it less dense.
Thus the depth of the oxygenated lens can vary according to the
degree of mixing. Such a lens would not be found during turnover
periods as turbulence would be sufficient to homogeneously mix the
two waters. The thickness of this lens supports the concept of
vertical flux by induced vertical turbulence.

Hamilton Harbour has a long history of receiving effluents of urban
and industrial origins. It has accumulated a high background oxygen
demand witnessed by the organic content, ammonia levels, and metal
concentrations in the water column. Studies of the oxygen demands
of Hamilton Harbour (Section B) have indicated that demands are
proportional to the oxygen concentration. This results in a
threshold supply rate at which oxygen must be available to increase
the oxygen concentrations in the water column. Natural mixing does
not supply dissolved oxygen at a rate to satisfy the oxygen demands
and build up a surplus of oxygen in the form of increased oxygen
concentrations.

With regard to total stock of oxygen, there is a depletion from 3.0
x 10^6 kg of oxygen in early May to 0.8 x 10^6 kg of oxygen by mid
to late June. As in 1975 (see Section B) there was a gradual
increase of stock during mixing. Original dissolved oxygen levels
were not achieved until after two months of thorough natural mixing
during the autumn overturn. This time lag to restore the oxygen
content could not be restored to saturated conditions in a period
less than two months. It should be remembered that during this
period the water is warm and the potential oxygen demand is at a
maximum.

Artificial mixing has definitely increased the oxygen stocks of the
harbour during the period of highest oxygen demand. The system is
not capable, however, of restoring dissolved oxygen at a sufficient

rate to overcome the oxygen deficit in a short period of time. Because of this, mixing must be initiated by the first week of May to avoid depletion. Because of the role of oxygen in biological production and waste assimilation an increase in stock by mixing favours the environmental management of the harbour waters.

Nutrients and Heavy Metals

A literature review (MOE, 1975) of the effects of artificial mixing on the chemistry of the water emphasized the importance of the oxidized microzone. This microzone, combined with oxygen enriched waters, can decrease nutrient and metal availability and even decrease metal concentrations by trapping these components in the sediment. Piccinin (1977) noted that soluble reactive phosphorus levels, (filtered reactive phosphorus) were lower after overturn in 1976 than in 1975. As total phosphorus levels were similar in both years this might reflect that aeration had altered the structure of the phosphorus compartments (see Barker 1976), although there was no biological evidence of the reduced availability of phosphorus.

Nutrient availability can be altered by the direct or indirect effects of artificial mixing. The direct effects are similar to the observations of Piccinin in altering the chemical state of a nutrient, and making it less available. An indirect but equally important effect is that mixing can limit production of algae, hence, affect the amount of nutrient utilized (Lorenzen and Mitchell, 1973). In artificially mixed systems nutrient utilization can be just as important as nutrient availability.

Nutrients

Filtered reactve phosphorus ranged from 2 ug/l to 48 ug/l, with the higher values being associated with the shallow stations 252 and 270. It is probable these values are related to wind disturbance of the sediments and the release of pore water phosphorus to the water column. This might account for some of the discrepancy between

Harris (1976) and Poulton (1977) regarding nutrient release from the sediments. As seen in Figure 5 there are distinct localized pockets of higher concentrations of filtered reactive phosphorus, particularly near the bottom of shallow stations. A similar pattern was seen in 1975 (MOE, 1976) with most pockets of available filtered reactive phosphorus being found in shallow water columns where wind energy could be directly transferred to the bottom sediments causing a stirring action.

Total phosphorus had a similar distribution being most patchy in shallow stations and tending to be more homogeneous with deeper stations. This aspect of the vertical structure of total phosphorus in deep water implies artificial mixing has reduced the high levels in the warm epilimnetic waters found in previous years. Phosphorus ranged from 38 to 118 ug/l, with higher values probably being associated with sediment disturbance (Figure 6).

Nitrogen response to artificial mixing was difficult to determine because of the high ammonia loadings to the basin. Nitrates range from 0.05 to 3.17 mg/l. The bottom waters had less nitrate than the upper epilimnetic waters during the summer (Figure 7). As nitrate was continually present at the sediment-water interface despite near anoxic conditions this strongly suggests high vertical transfer rates of nitrate possibly associated with artificial mixing. This hypothesis is supported with the high summer nitrate values at the bottom of Station 258 (near the diffusers, see Figure 7) from 0.78 to 3.17 mg/l. Such conditions might favour nitrogen formation (see Snodgrass 1977) at the sediment-water interface.

Nitrite did not show any of the large accumulations which were evident in 1975. Values ranged from 0.03 - 0.34 mg/l, and appeared to have two active phases during 1976 (Figure 8). The first was in early June, when the oxgyen stocks were being rapidly depleted.

Towards the end of August there was second accumulation of nitrite at all four stations. These pulses of nitrite were not related to artificial mixing, but might reflect a period during the spring thermal stabilization and autumn turnover when the harbour system adjusts from oxic to anoxic respiratory states and vice versa.

Ammonia followed a trend similar to previous years with high spring concentrations of 3.02 mg/l gradually decreasing over the year to 0.01 mg/l (Figure 9). This decrease in the average ammonia concentration in the water column is consistent with an increase in the heat content. A scatter plot of average ammonia concentration against average water column temperature (Figure 10) up to the time of maximum heat content supports this theory. It is apparent that because of hypolimnetic warming by artificial mixing the heat budget of the harbour will be increased. This is apparent at Station 258 where hypolimnetic temperatures of $13^{o}C$ were achieved. As mixing would increase the heat budget, ammonia could be stabilized at a greater rate. Ammonia remained a key environmental concern as levels continued to increase from late October until June the following year. During this time at least 5.6×10^{8} g NH_3 were added to the harbour waters, suggesting loadings of 2.6×10^{6} grams per day (0.12 g/m^2/d). This situation cannot be altered by artificial mixing, as the harbour loadings are well beyond the ammonia assimilation potential of the harbour particularly during the winter period when nitrification is limited by temperature. These figures are lower than original ammonia loadings estimates (MOE 1974) of 10.9×10^{6} g/d, but illustrate that further reductions of ammonia loadings particularly during the winter periods are required.

Total Kjeldahl nitrogen declined during the year similarly to ammonia (Figure 11). Levels declined until the end of October, and started to increase initially at Station 4, then by mid November increases were noted across the harbour. The organic nitrogen component (TKN-ammonia) is very small, and showed no response to mixing, probably because there was no major redistribution of phytoplankton, bacteria or detrital material.

Because of their relatively high loadings, phosphorus (approx. 2 $mg/m^2/d$) and nitrogen (approx. 120 $mg/m^2/d$) have little effect on the primary production of the harbour. Silica, however, has been suggested as a possible control (Piccinin, 1977; MOE 1977) method available to manage algal production in the harbour. Silica values during 1976 ranged from 0.05 to 1.25 mg/l. As mixing would stimulate phytoplankton production, in particular diatoms which incorporate silica as a cell wall component, silica could well be a limiting factor. Happey (1969) reported that 1 mg/l of $SiO2$ could support 10^6 cells of moderate sized centric diatoms (i.e. 5.0 x 10^3 um^3). Similar associations have been found by Hughes and Lund (1956), and would imply that despite the possibility of a silica buffering system (Cheng and Tyler, 1971) and the possible sediment release of silica even under oxic conditions, diatom crops could be limited to below 10^6 cells/l (5.0 x 10^{10} um^3/l).

Observations of the spring diatom growths in 1975 and 1976 (see Section E) have suggested crop limitations to be related to silica depletion and increased sinking rates. Artificial mixing would merely extend the growth period of these diatoms until silica depletion occurs. As these populations would be homogeneously dispersed through the water column, actual cell or chlorophyll concentrations would remain low (15 ug/l).

Figure 12 indicates vernal depletion of silica at Stations 252 and 4. Station 270 does not have as definite a decline in silica, and Station 258 has an abundant supply of silica at the time of the spring minimum of silica. It would be this supply of silica in the central basin which sustained small diatom crops during the summer period. The late summer peak in mid-August in the eastern end of the harbour was not related to any observed natural causes such as rainfall, sediment disturbance or change in structure of phytoplankton populations.

Metals

Metals had been monitored intensively in 1975 and many were found in
concentrations too low to state if they changed as a result of
artificial mixing. During 1976 only a few metals were chosen with
regard to the effects on biota and concentrations found 1975.
Copper was low (less than 0.001 mg/l) and not considered to be an
environmental hazard. Manganese concentrations were higher (0.02 to
0.20 mg/l) but again were not considered to be a hazard. The higher
values were from the bottom waters at Station 270 in early October
and this probably represents sediment disturbance either by wind or
the approaching Kemmerer sampler. It must be emphasized, however,
that low metal concentrations do not prevent bioaccumulation. Fish
flesh analysis to date does not indicate environmental problems of
Ca and Mn.

The two major metals of environmental concern in the water of
Harbour are iron and zinc. Figure 13 illustrates zinc levels which
continuously exceeded the IJC water quality objective of 30 ug/l.
Spatial variations were highest from May until the end of July. As
the loadings of zinc are probably point source in nature, high
heterogeniety is expected. The maximum effective loading of zinc
was calculated to be 72mg $Zn/m^2/d$. There was no apparent effect
of artificial mixing on zinc levels or distribution.

Iron levels frequently exceeded the IJC objective of 300 ug/l and
was heterogeneously distributed throughout the year (Figure 13).
The effective loading from early June to the middle of July was 201
g $Fe/m^2/d$, thus the heterogeniety is explained by these high
inputs. As in 1975 there was not the facility to measure the
dissolved iron component, and thereby assess the chemical effects of
aeration on redox potentials of the harbour.

pH, Alkalinity, Conductivity and Redox Potential

There were not significant changes in conductivity (430 to 600 micro Siemens per cm) which can be associated with the mixing system. Conductivity decreased during the year. The high spring concentration is probably a function of snowmelt and runoff from roads followed by gradual dilution by advective flow and mass exchange through the ship channel.

In some instances (MOE, 1976), changes in pH have been noted where artificial mixing has been used as an environmental management technique. These changes are usually restricted to soft water lakes with little buffering capacity or decreased photosynthetic activity. As Hamilton Harbour waters are well buffered (alkalinity of 135 to 90 mg $CaCO_3$/litre), little change in pH can be expected as little CO_2 would be purged by the mixing system. During 1976, pH ranged from 7.4 to 8.3 and similarly to alkalinity and conductivity, decreased during the year.

Apparent redox potential profiles were utilized in 1975 to illustrate the effects of artificial mixing. Clinograde profiles of the redox potential were altered 1975 and became more homogeneously distributed with depth. As clinograde profiles were not observed in 1976, a similar comparison could not be made (Figure 14). Redox potentials revealed great flux during the period of artificial mixing (Figure 15). These rapid changes in apparent redox potential may reflect lake-harbour exchanges more than mixing effects. The low redox potential of the harbour water indicates a weak reducing capacity - i.e. ability to give off electrons - which is probably related to the abundance of reduced sulphur compounds, ammonia, nitrite, magnesium^{2+} iron^{2+} and organic compounds. It is probable that the intensity and capacity of oxygen consumption (oxidation) are related as Hargrave (1972) found that the square root of oxygen uptake in sediments was inversely correlated with redox potential. Thus redox potential could be a sensitive measure of long term effects of mixing.

Turbidity, Suspended Solids, and Carbon

The gray waters of the harbour have only moderate turbidity levels
(1.5-2.3 Formazin units) (Figure 16) with the higher values being
related to sediment disturbances by strong winds in early spring.
During the period of artificial mixing, turbidity values range 2.5
to 4.5 but no definite pattern could be related to mixing or
disturbance of the sediments either by the diffuser or the vortex
generator. There was a linear relation between turbidity and
suspended solids.

$$\text{Turbidity} = 0.97 \ (\text{suspended solids}) - 1.73;$$

with a correlation coefficient of $r = 0.76$. Perhaps the most
interesting aspect of this regression is that when turbidity is 0,
the predicted suspended solids content of the harbour is 1.78 mg/l.
This suggests that particles less than 2 um were abundant.
Particles smaller than this size have a forward scattering effect on
penetrating light and therefore are not measured as turbidity. To
achieve the high vertical attenuation of light (=1.7) common to the
harbour and represent 20-30% of the suspended solids, these small
particles play a very important role in biological production.
Because of their size these particulates probably do not settle out
as their sedimentation rates are extremely low. This is verified as
the vertical attenuation of light during 1976 ranged from 0.81 to
1.86, with the upper values being dependent on algal growth.
Minimum values of remained high because of small particulates and
organic colouring.

With regard to the mixing project, these particles cannot be managed
unless there is biological utilization of them. This utilization
might include zooplankton grazing, bacterial breakdown or
heterotrophic assimilation of colloidal carbon. Aeration would
stimulate these activities by increasing the zooplankton habitat,
and maintaining an environment for heterotrophic bacteria, protozoa
and phytoplankton.

Such biological assimilation however, depends on much of the material being organic. Suspended solids ranged from 3.0-11.0 mg/l, and particulate organic carbon (total organic carbon - filtered organic carbon) ranged from 0.0 to 2.5 mg/l. There was a correlation between POC and suspended solids with a correlation coefficient of $r = 0.68$ such that

$$POC = 0.58 \text{ (suspended solids)} - 2.41 \quad .$$

As 20-30% of the total organic material is bacterial and algal in nature (MOE 1977), the remaining fraction must be small particulates, colloids or dissolved organics. In comparison to the range of values of particulate organic carbon, filtered organic carbon is much higher, and possibly includes many small particulates which could pass through the filter. Filtered organic carbon values range from 1.5 to 9.75 mg/l which would suggest that most of the fine material is organic, and that artificial mixing could help in the stabilization of this component.

BIOLOGICAL RESPONSES TO ARTIFICIAL MIXING

Bacterial Populations

Responses of bacteria to environmental modifications are not frequently reported in the literature. Little is known of the habitat preferences of naturally occurring bacteria such as the heterotrophs, thus it is not possible to compare the results of Hamilton Harbour to other situations. Emphasis is usually placed on pathogenic indicator species with regard to health problems, and not on bacteria as mechanisms of self purification, waste assimilation and nutrient utilization.

Bacterial populations in 1975 indicated that the effects of mixing included vertical displacement of bacteria, decreasing surface concentrations, and possibly stimulated growth of heterotrophs and sulphur oxidizers. These observations were not confirmed because of the limited period of mixing, although it is difficult to associate these changes with other environmental parameters.

The most notable trend in bacterial populations during 1976 was a continued decrease in fecal coliform organisms at all stations. This decline was apparent at all depths, although the surface values at Station 258 fluctuated widely. In general, over the year of 1976, the bacterial populations, as indicated by fecal coliform determinations, would suggest that Hamilton Harbour waters were within the criteria for body contact recreation.

Most stations (4, 270, 258, 252) and depth samples illustrated similar trends at any one time of the year. Station 4, because of its proximity to the Windermere basin, frequently had the highest abundance of heterotrophs and other bacteria monitored (fecal coliforms, sulphur oxidizers, sulphate reducers and Nitrosomonas). The fact that the same station can have the highest count of both sulphur oxidizers and reducers reflects the complex spatial and temporal patterns which are encountered in coastal waters.

Station 252 being only 6 m deep, is well mixed and frequently exhibited homogeneity with depth. Figure 17a illustrates a general decrease of fecal coliforms and heterotrophs at 0.2 m and 6 m depth. Sulphur oxidizers had a large summer population (3.5×10^8 counts/l) near the surface, and a late summer pulse (1.1×10^8 counts/l) near the bottom. There were no discernible trends of Nitrosomonas at this station. Excluding the sulphur oxidizers, all taxa declined moderately in comparison with the 1975 data, particularly the heterotrophs which dropped from 8.0×10^5 counts/l to 5.8×10^5 counts/l. In contrast to this, the sulphur oxidizers increased from 8.5×10^4 to 10.0×10^7 counts/l. This large increase of population is difficult to explain, although the

increase was noted at the end of the mixing period in 1975. There were no substantial differences in the apparent redox potentials from 1975 to 1976, and there is no evidence to suggest a chemical or physical change in the harbour environment directly related to these large fluctuations in composition and abundance of bacteria. A change in culture technique was reported, but this would not account for such large population increases.

Station 4 had similar bacterial population changes to Station 252 although more abundant. Fecal coliforms, sulphur reducers and Nitrosomonas decreased throughout the year at 0.2, 6.0 and 18 meters depth. Heterotrophs showed a similar decline during the year, but were as abundant during 1976 as in 1975 (geometric mean of 1.7 x 10^6 counts/l in 1975). Sulphur oxidizer populations were very large at Station 4 (5.8 x 10^7 counts/l as compared to 1975 determinations of 9.9 x 10^4 counts/l) (Figure 17b).

For both 1975 and 1976, Station 258 had the smallest populations of pathogenic indicator species which tended to decline during the summer. Crops of heterotrophic bacteria declined from 6.9 x 10^5 to 4.4. x 10^5 over the year, and decreased with depth during 1976 unlike the 1975 survey results (see Figure 17c). As in situ production would require oxygen and the facultative use of light, the lower waters would not favour the development of heterotrophic bacteria. Sulphur oxidizer populations were larger in 1976, (1.1 x 10^6/l as compared with 1975 of 8.8 x 10^4/l), and showed a definite increase with depth. This is expected as these bacteria oxidize H_2S either by utilizing oxygen or nitrates. As the co-existence of H_2S and oxygen is rare, these bacteria are frequently associated with hypolimnia with unstable thermal layers (Goltermann 1975), and hence are highly favoured in the harbour environment during the periods of artificial mixing.

The temporal distribution of _Nitrosomonas_ in Hamilton Harbour is
erratic. It is apparent in the literature that the conversion of
ammonia to nitrite by these bacteria can be inhibited, but actual
mechanisms remain in question. Such inhibition, if present in
Hamilton Harbour, could explain the lack of pattern in distribution
and abundance of these bacteria in the Harbour waters. Possible
mechanisms for such inhibition are substrate levels and toxicity.

Station 270 had the smallest population of sulphur oxidizers and
heterotrophs. Lack of substrate (either organic molecules or
reduced sulphur compounds) might well be important at this station.
Fecal coliforms and _Nitrosomonas_ were low (Figure 17d).

Table 1 outlines the geometric means of bacterial samples at
different depths at the four major stations. This emphasizes the
abundance of sulphur oxidizers over the other forms of waste
assimilation capacity of the harbour. These bacteria provide one of
the few processes by which the large amount of allochthonous carbon
can be stabilized. Mixing has not had any definite effect in
stimulating the heterotrophic bacteria of the harbour. Thus the
assimilative capacity of the harbour (both biological and chemical)
has not been sufficiently stimulated by the mixing project.

Phytoplankton

The structure and distribution of phytoplankton populations are
illustrated in Figure 18 using chlorophyll _a_ as an estimate of algal
abundance. As in previous years, chlorophyll _a_ levels remain high
at 20 to 30 mg/l, but still do not reflect fully the hypertrophic
nature of the harbour waters. Generally, the vertical structure of
chlorophyll indicates large variations over time, and it is
difficult to isolate any event which directly relates to the
artificial mixing program. The diffused chlorophyll _a_ gradients
indicate the phytoplankton are exposed to a wide range of mixing
depth and this physical stress is limiting production within the
harbour waters. This hypothesis will be more fully discussed in the
following paragraphs.

The general seasonal variation is initiated by a diatom growth of
Stephanodiscus hantzschii Grun, during periods of no thermal
stabilization (Figure 19). This is followed by a mosiac of species
of Cryptomonas (erosa, ovata, rostratiformis) which becomes
established during the initial stages of thermal stabilization
(Figure 20). These algae apparently do not depend solely on light
as their chlorophyll cell volume ratio is low. They do become
limited to the upper layers in the later stages of stabilization
(June 1976) because of oxygen depletion in the hypolimnion.

During July there is rapid flux of species. This period is
characterized by erratic changes in the mixing depth because of
physical perturbation of coastal areas. Professor G. Harris of
McMaster University reported that phytoplankton of the harbour had
high levels of phaeophytin (the pigment indicating break-down of
chlorophyll a). This strongly implies that vertical mixing was
limiting the photosynthetic capacity of the phytoplankton. Periods
of unstable mixing conditions had an abundance of species, but few
illustrated the ability to adapt to the rapid physical-temporal
variations.

Despite this period of rapid change in composition, crop levels
remained consistent. This species variability in composition would
not be noted using chlorophyll a as an indicator of phytoplankton
population structure. During the July period, Chlamydomonas, a
small flagellate was the major phytoplankton species (Figure 21)
which could adapt to the erratic changes of mixing depth. This is
probably because it could maintain its own photic depth or was
capable of heterotrophic assimilation of carbon.

In August a temporally stable thermal gradient was developed and
Oocystis borgei became dominant in the early part of the month
(Figure 21). Fragilaria crotonensis became more abundant towards
the latter part of August (Figure 19). As this diatom was dependent
on vertical turbulence to remain in suspension, this emphasizes the

importance of the physical forces which are actively modifying the biological nature of the harbour environment. After the autumn overturn the large-centric diatom _Stephanodiscus astraea_ became abundant when natural mixing was sufficient to overcome its naturally high sinking rates.

During the August period a diffused thermal gradient developed and was dependent on the continuous operation of the artificial mixing system. As diatoms were present (and at times abundant), during this period, the physical modifications by mixing probably favour their development. The more important aspects of this observation are that diatom growths can be stimulated despite the warm water temperatures, and algal production in the harbour can be managed by the direct physcial effects of artificial mixing. This lessens the importance of phosphorus-nitrogen loadings to the harbour as nutrient utilization would become much less efficient. Under fully mixed conditions chlorophyll _a_ concentrations should decrease and phytoplankton production may become silica limited.

Productivity was measured with regard to gross oxygen production (light and dark bottle method) and carbon assimilation (^{14}C incubations). The former method indicated productivity was 5.3-79.3 mMO_2/m^2/hour and the latter suggested values of 3.8-15 mM C/m^2/hour. It is quite possible the oxygen technique had over-estimated productivity on two occasions (see Table 1, Section E.) when dark bottle respiration was high. There were no definite responses of productivity to artificial mixing. The oxygen data would suggest that productivity is higher during periods of homogeneous mixing in the spring. This would be related to the growth of _Stephanodiscus hantzchii_ which would be well adapted to periods of high turbulence and constant mixing depth. The summer productivity is lower, although there is some evidence of an increase to 180 mg Carbon/m^2/hour towards the end of July when aerator flows of over 0.14 m^3/sec were achieved. Because of the high nutrient loadings discussed previously, changes in productivity are more likely related to changes in mixing depth, adaptiveness of existing populations and changes in the quality and quantity of the penetrating light, than to nutrient levels.

Zooplankton, Benthos and Fish

Zooplankton was only monitored by McMaster University and results have been discussed by Piccinin (1977). A larger habitat existed for exploitation by zooplankton during 1976, but oxygen stress was still very much in evidence.

During 1976 zoobenthos was dominated by oligochaetes, with some possibility of increased numbers as a result of decreased ammonia toxicity.

Fish data were not fully available at the time of this report, excluding an abstract by Mr. D. Howell (Ministry of Natural Resources, Cambridge, Ontario) indicating that the compositon of the fish populations of Hamilton Harbour were suited to situations of low oxygen tensions. To date, there are no data available on fish toxicity and possible changes in toxicity caused by artificial mixing.

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TABLE 1

Bacterial Populations of Hamilton Harbour

1976

(Geometric means over the year)
counts/100 ml

	Surface	Middle	Bottom (20m)

Station #4

	Surface	Middle	Bottom (20m)
Fecal Coliforms	98	70	38
Heterotrophs	171,374	42,443	36,917
Sulphur Oxidizers	5,838,263	910,582	263,502
Sulphur Reducers	227	66	49
Nitrosomonas	735	2,407	2,683

Station #252

	Surface	Middle	Bottom (20m)
Fecal Coliforms	23	–	73 (6m)
Heterotrophs	58,749	–	81,779
Sulphur Oxidizers	996,767	–	344,449
Sulphur Reducers	107	–	238
Nitrosomonas	910	–	832

Station #258

	Surface	Middle	Bottom (20m)
Fecal Coliform	51	43	13 (20m)
Heterotrophs	94,546	20,793	21,901
Sulphur Oxidizers	107,015	150,243	223,882
Sulphur Reducers	22	14	20
Nitrosomonas	741	197	1,293

Station #270

	Surface	Middle	Bottom (20m)
Fecal Coliform	77	25	36 (12m)
Heterotrophs	31,690	16,355	23,837
Sulphur Oxidizers	58,889	83,889	128,923
Sulphur Reducers	51	40	38
Nitrosomonas	426	719	577
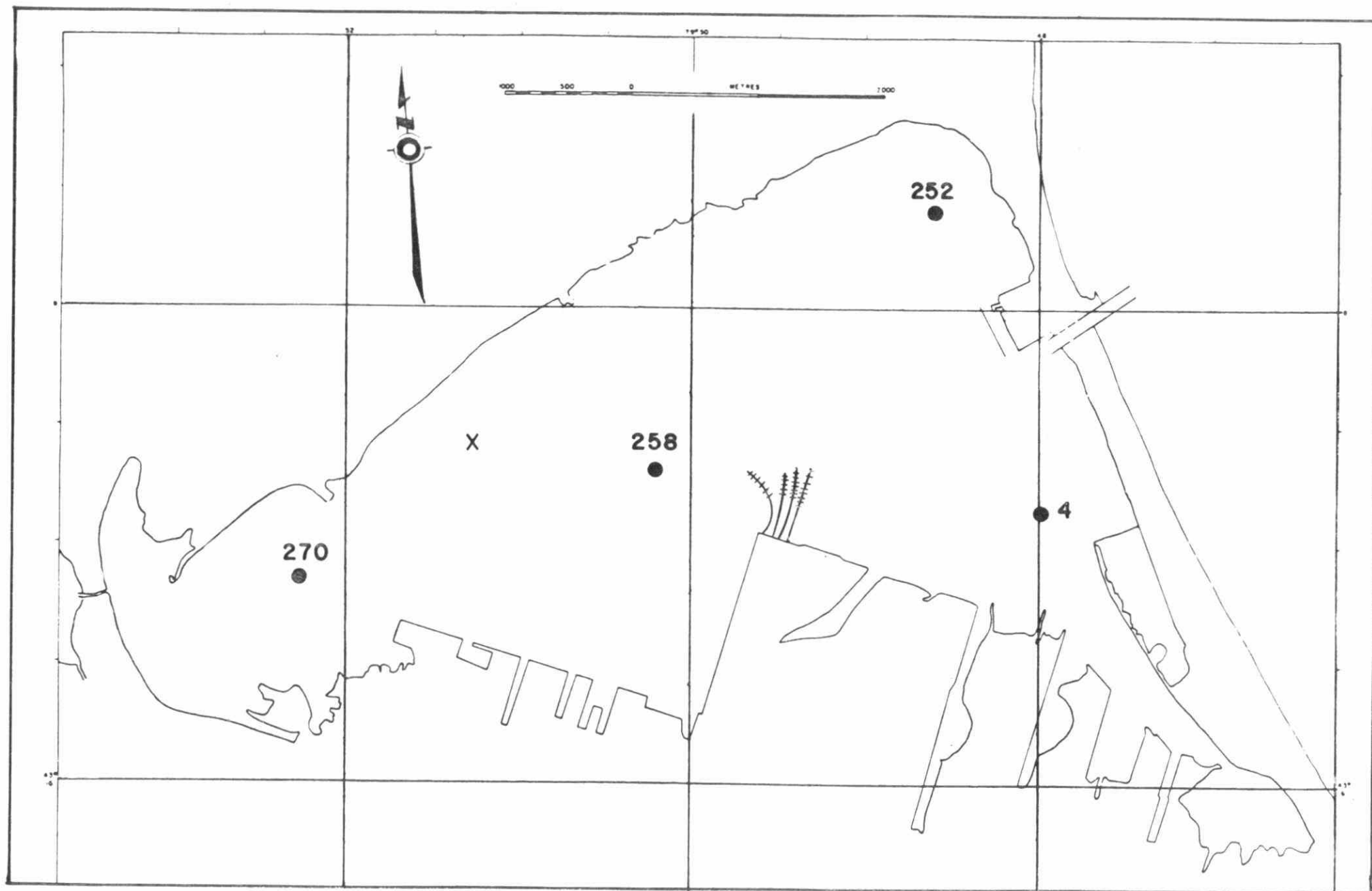
FIGURE 1 : HAMILTON HARBOUR ILLUSTRATING DIFFUSER LINE, POSITION OF VORTEX GENERATOR AND MAJOR SAMPLING STATIONS.

A-25
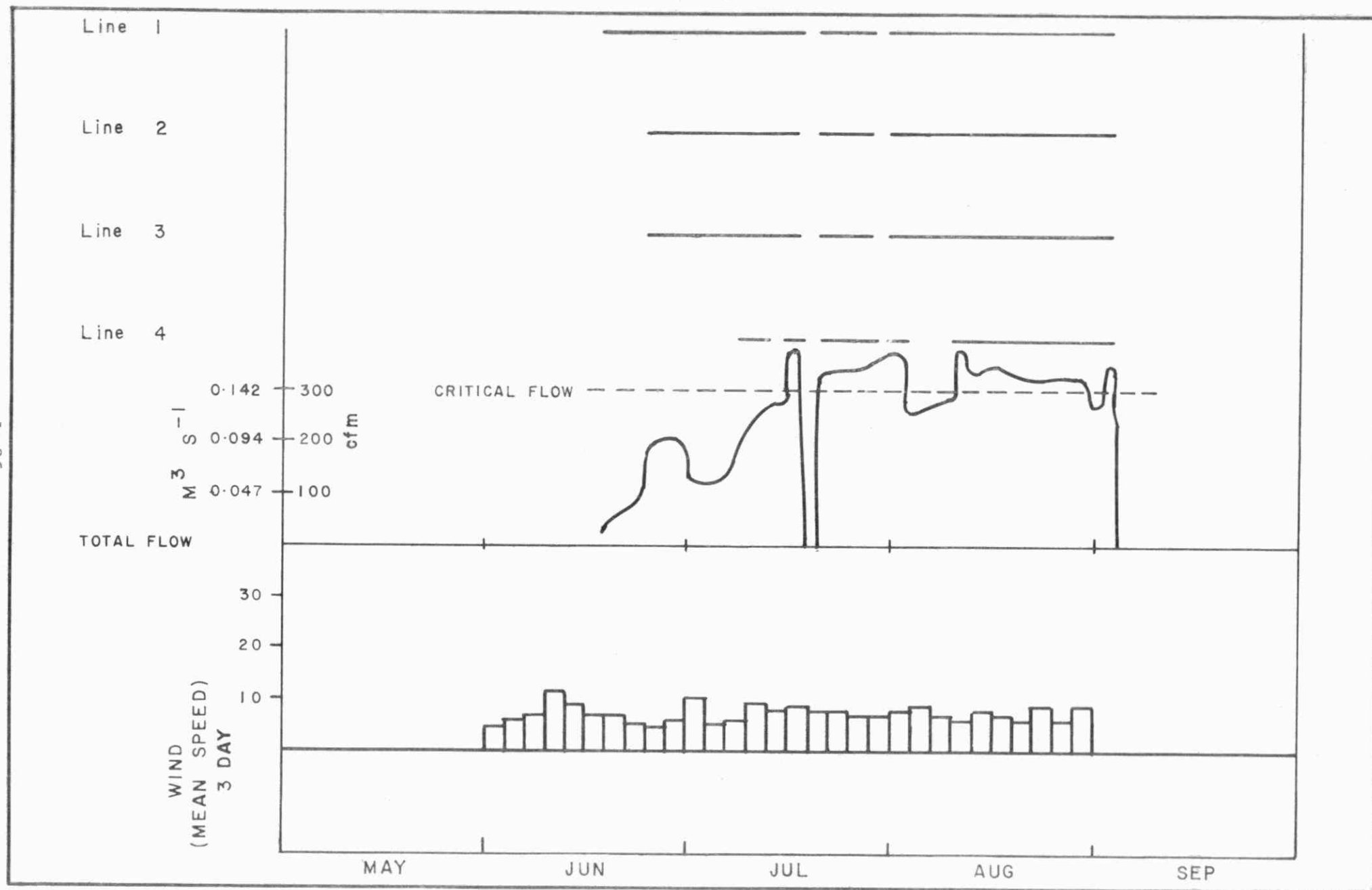
FIGURE 2 : SCHEDULE OF OPERATION OF DIFFUSER LINES AND WIND ACTIVITY. HAMILTON HARBOUR 1976
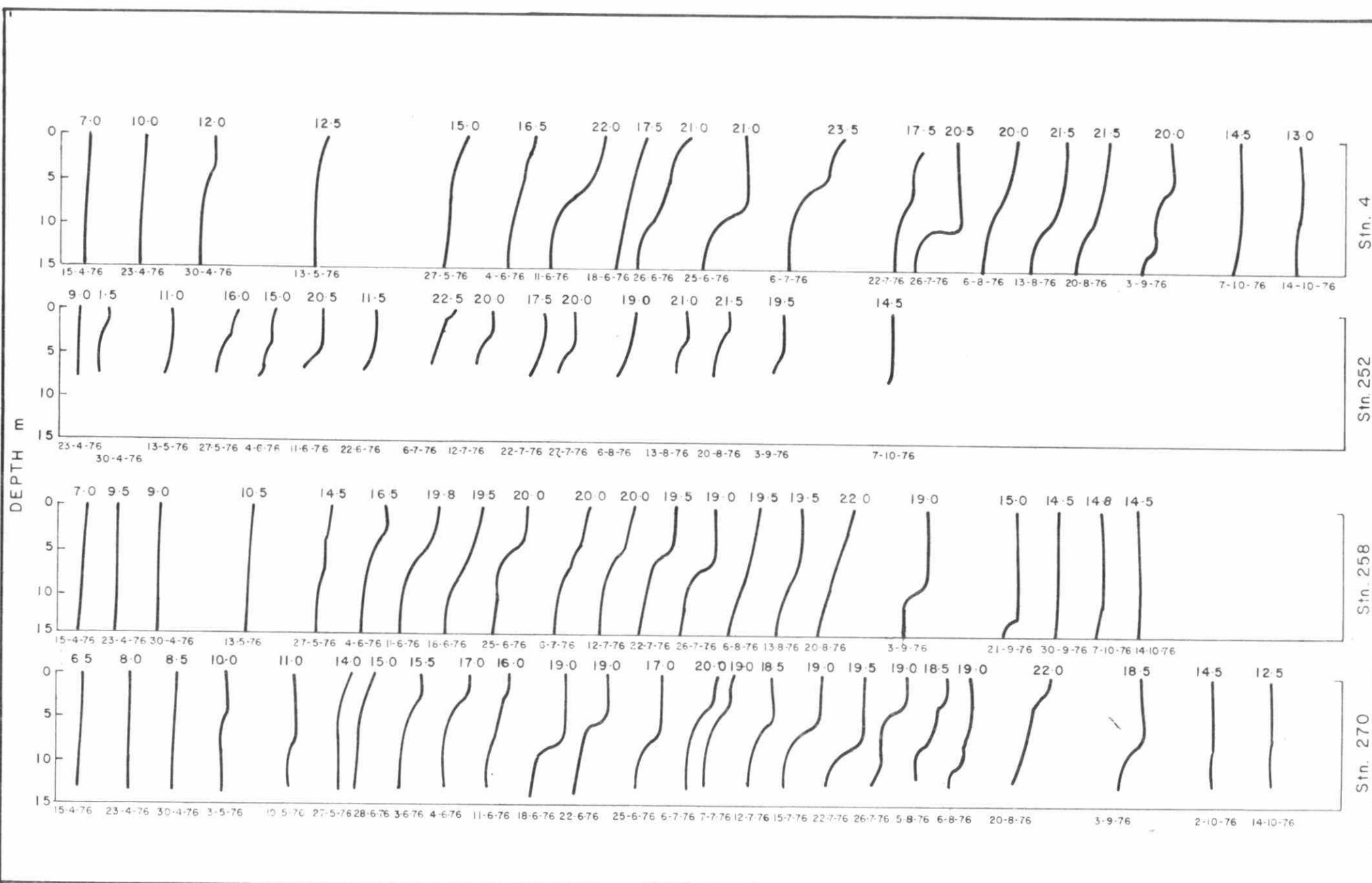
FIGURE 3 : TEMPERATURE (°C) DEPTH PROFILE AT MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976
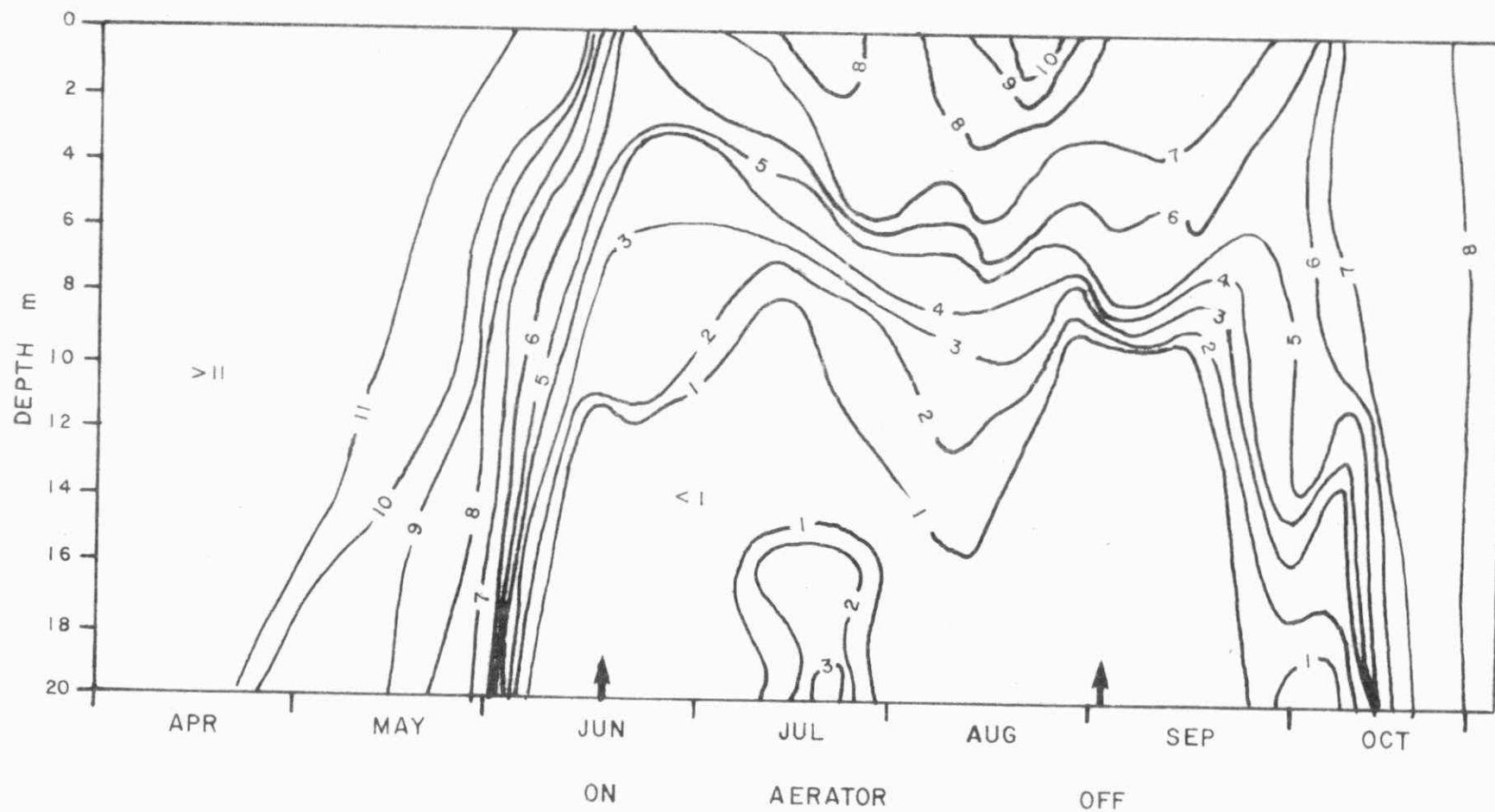
FIGURE 4a : DISSOLVED OXYGEN PROFILES (mg/l). HAMILTON HARBOUR 1976 STATION 258.

A-28
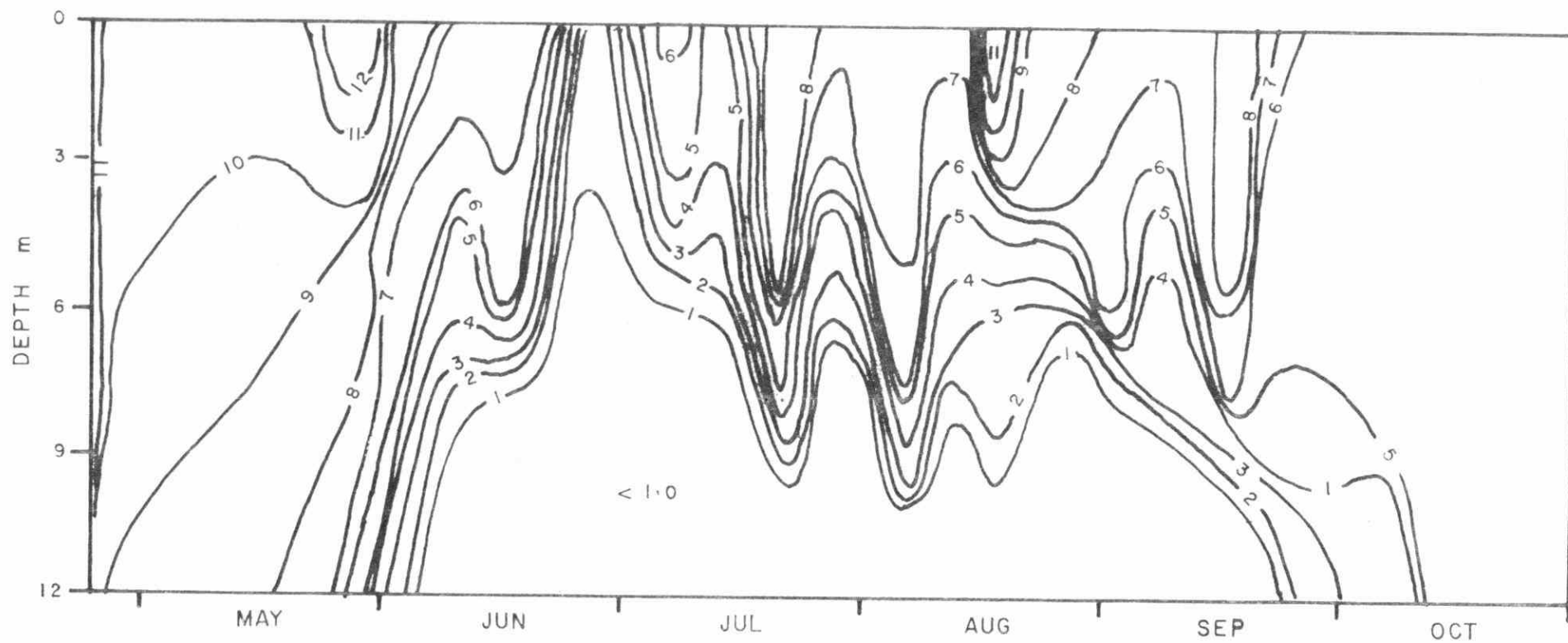
FIGURE 4b : DISSOLVED OXYGEN PROFILES (mg/l), HAMILTON HARBOUR 1976 STATION 270

A-29
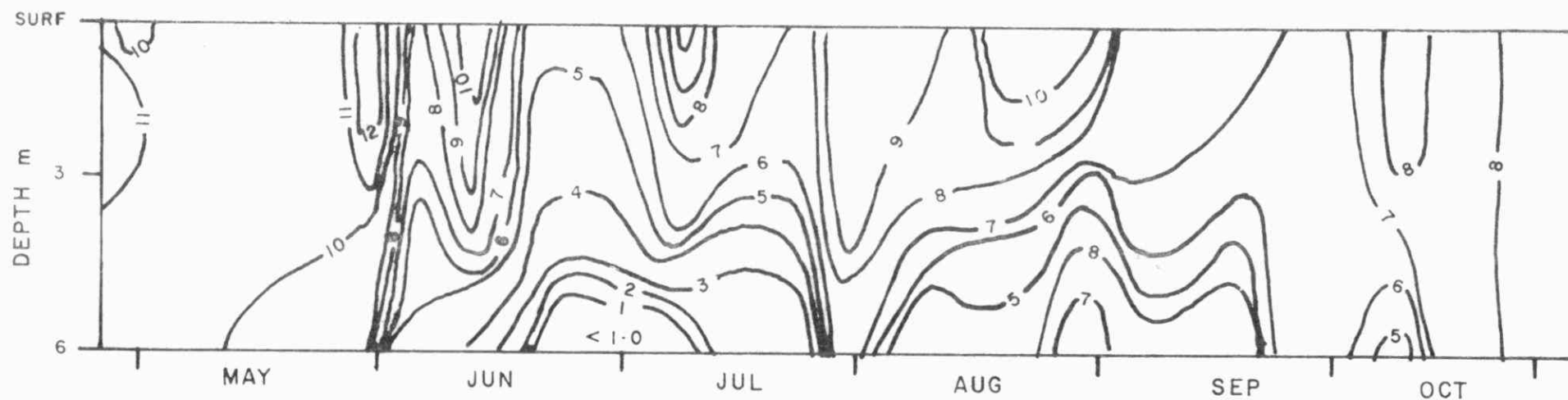
FIGURE 4c : DISSOLVED OXYGEN PROFILES (mg/l) HAMILTON HARBOUR 1976 STATION 252

A-30
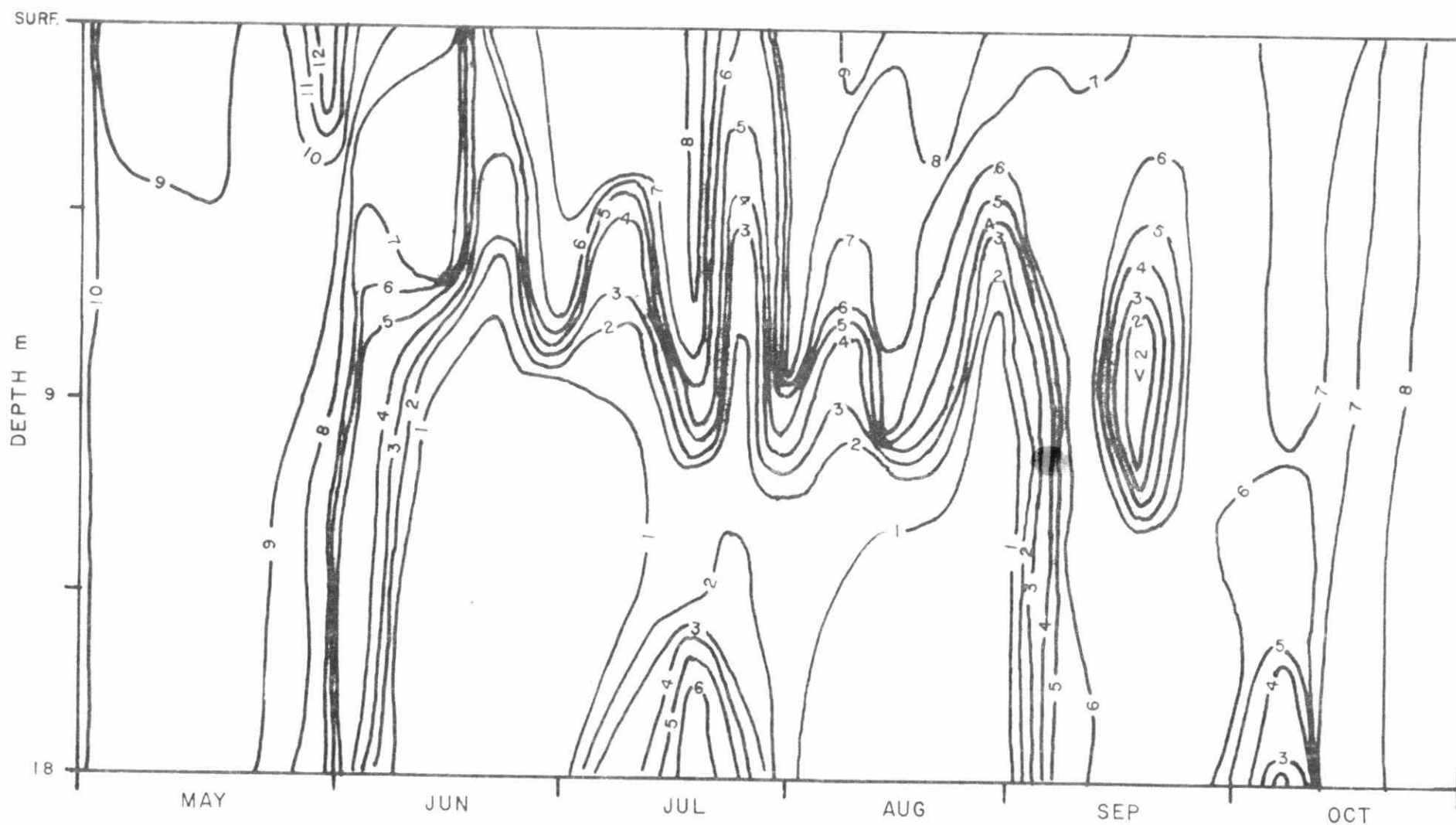
FIGURE 4d : DISSOLVED OXYGEN PROFILES (mg/l) HAMILTON HARBOUR 1976, STATION 4.

A-31
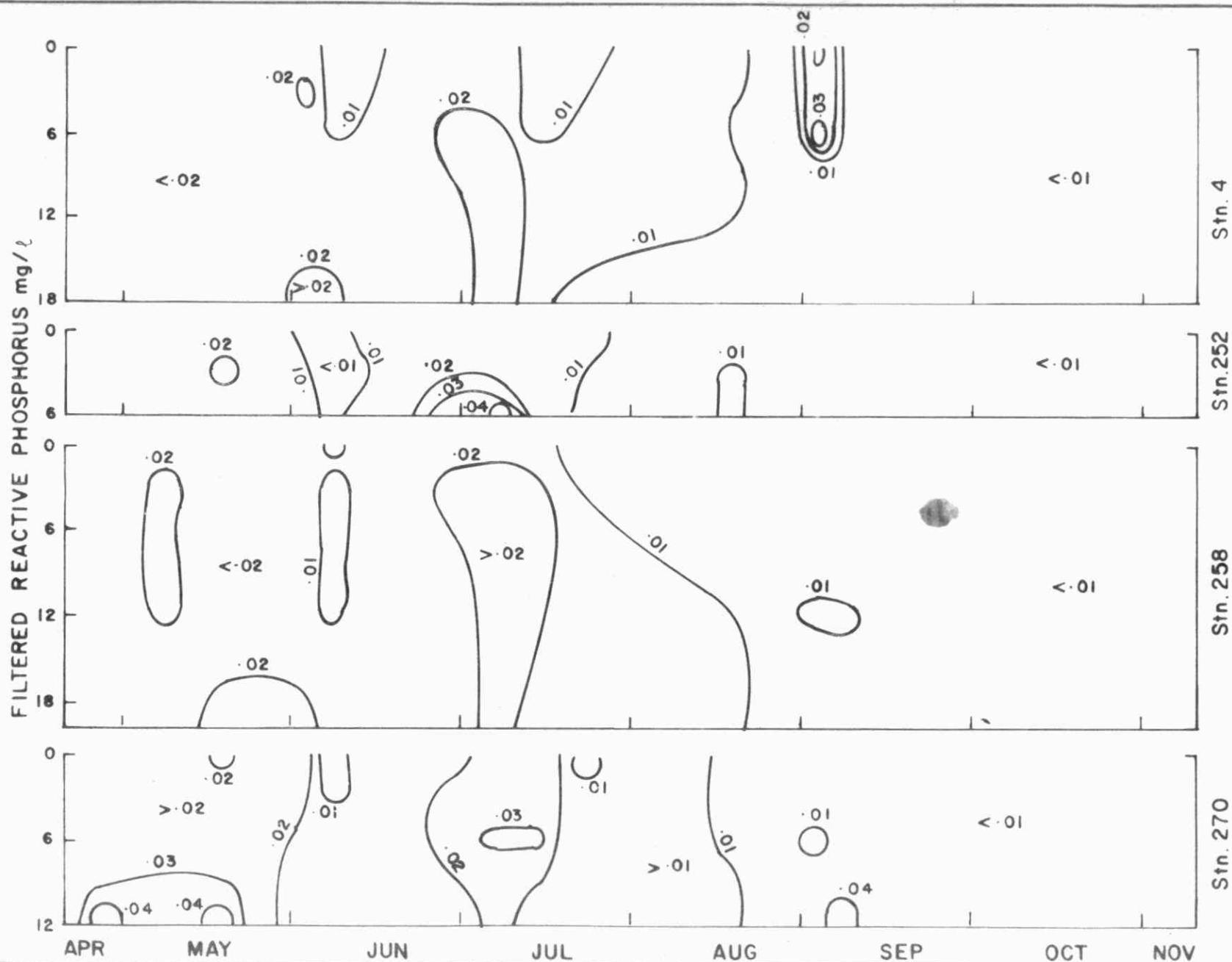
FIGURE 5 FILTERED REACTIVE PHOSPHORUS ISOPLETHS, AT MAJOR SAMPLING STATIONS, HAMILTON HABOUR 1976

A-32
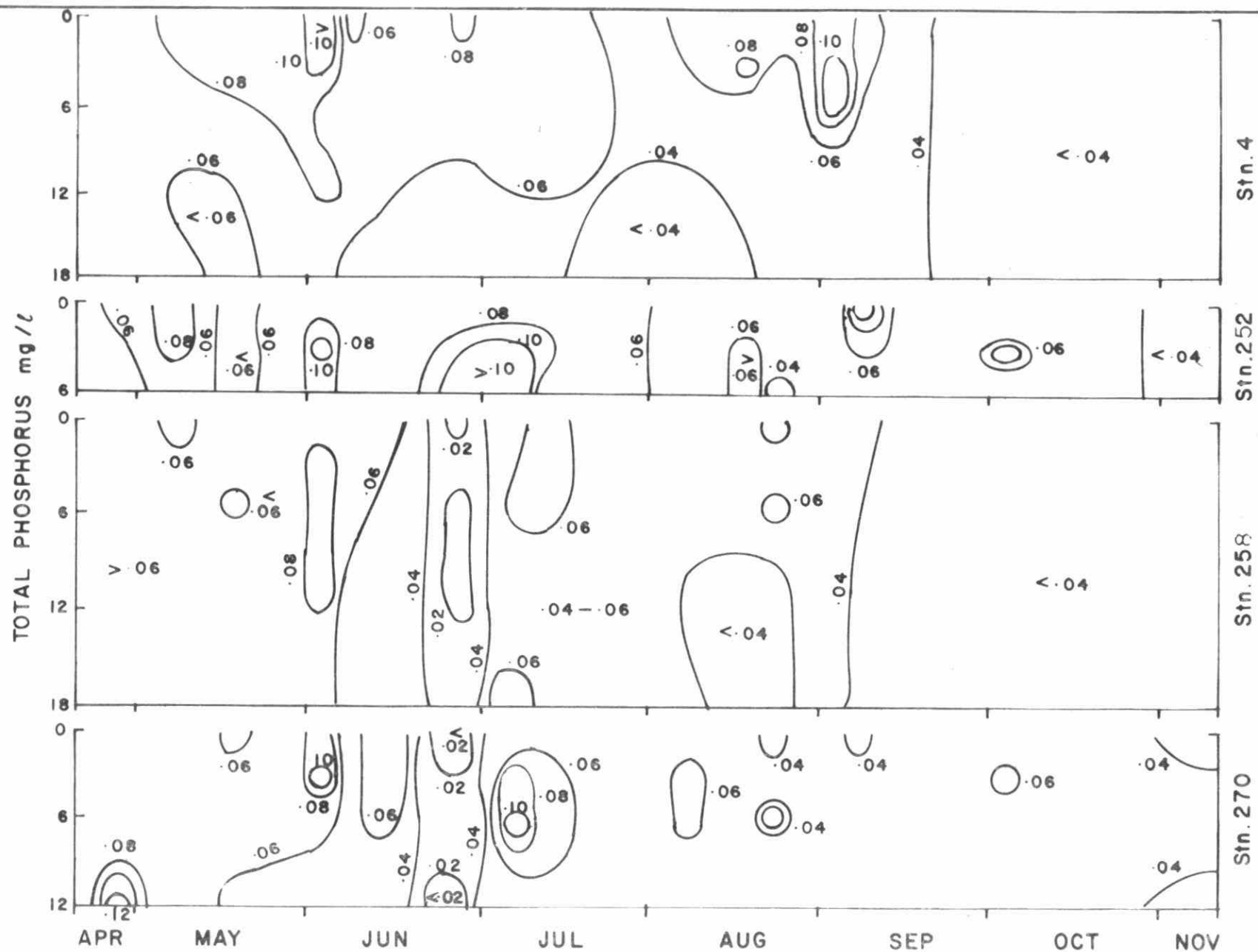
FIGURE 6 : ISOPLETHS OF TOTAL PHOSPHORUS mg/ℓ AT MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976.
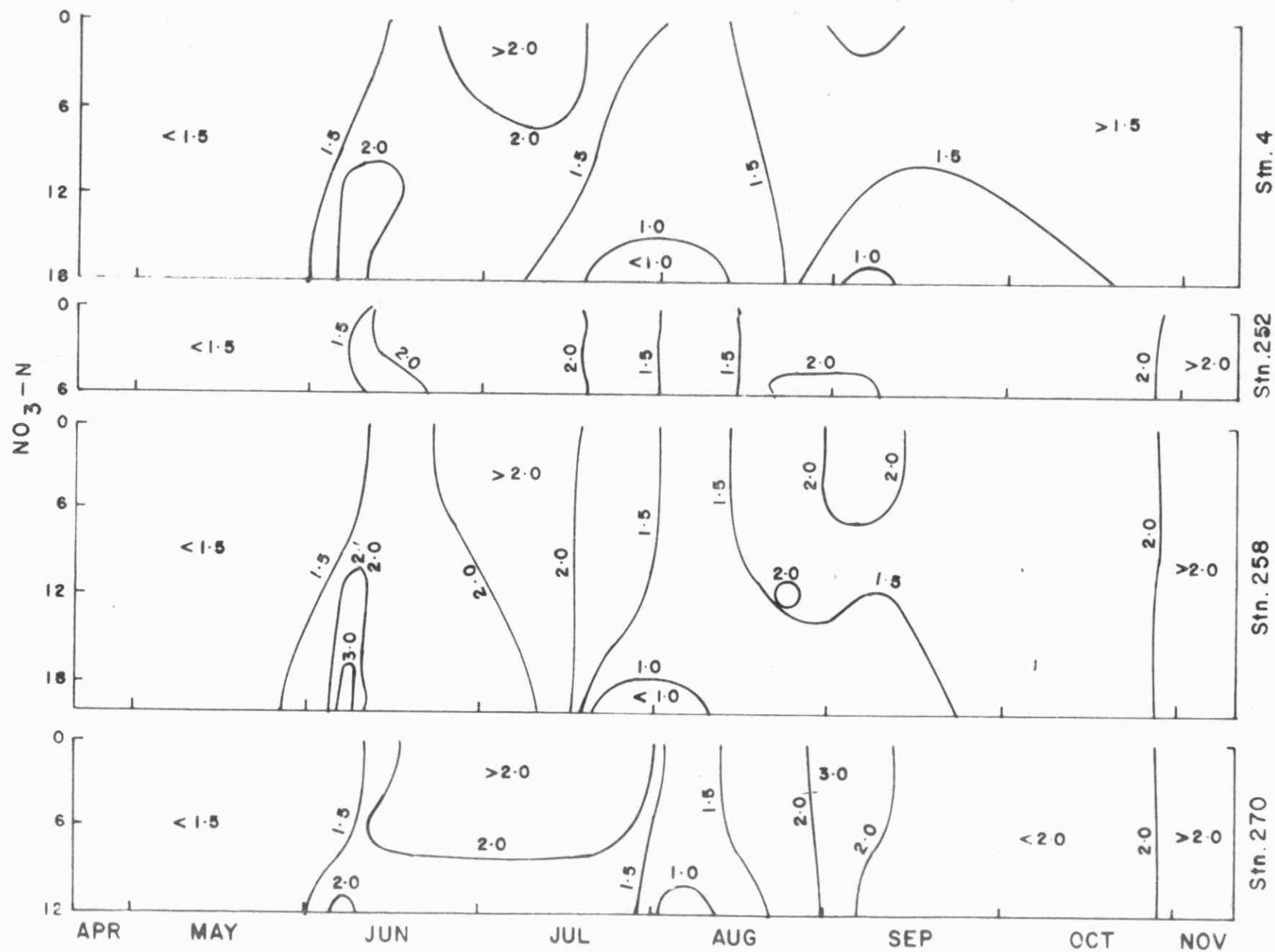
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FIGURE 7 : ISOPLETHS OF NITRATE (mg/ℓ) AT MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976
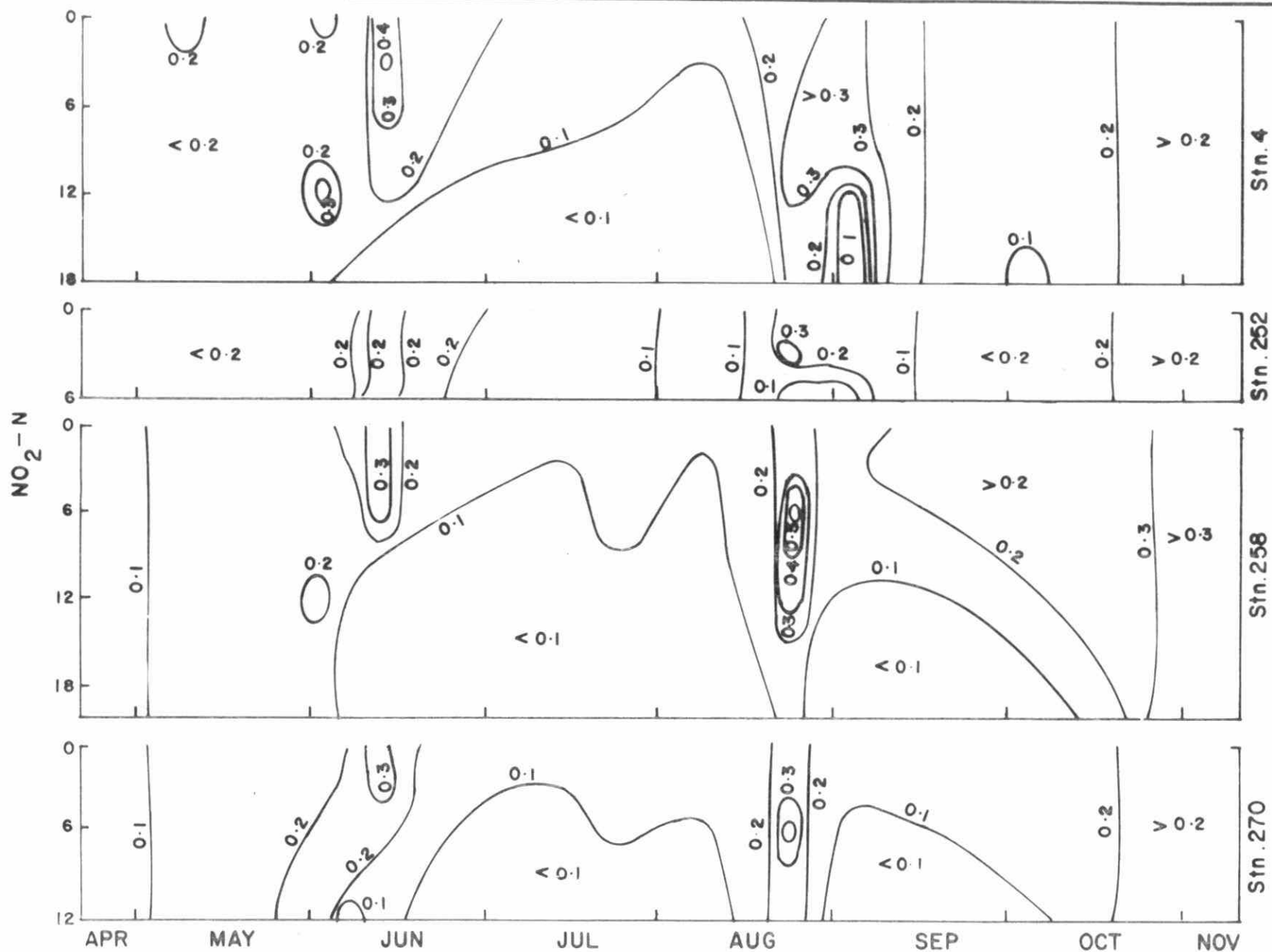
FIGURE 8 : ISOPLETHS OF NITRITE mg/ℓ AT MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976

A-35
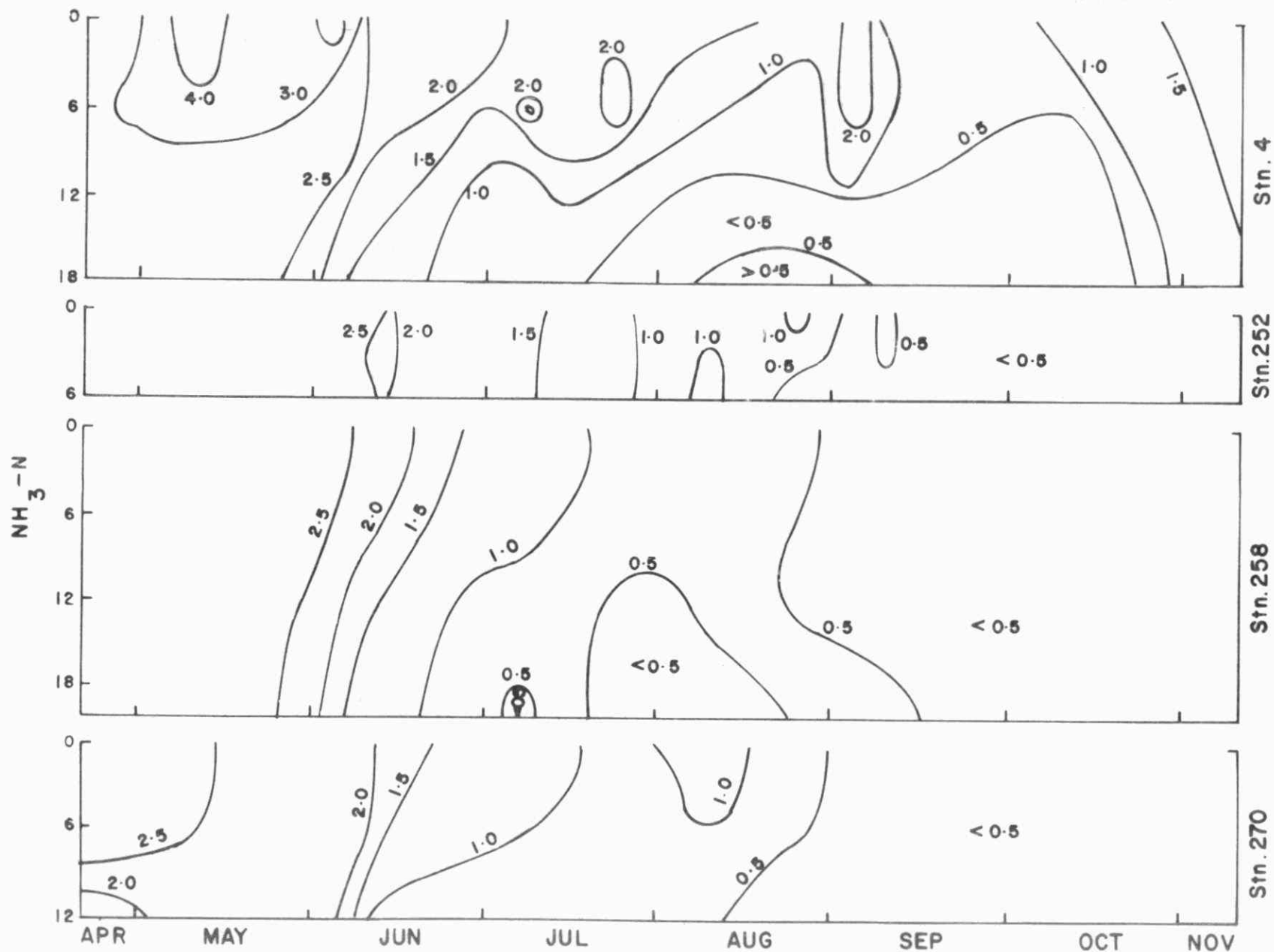
FIGURE 9 : ISOPLETHS OF NH₃ (mg/ℓ) AT MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976

A-36
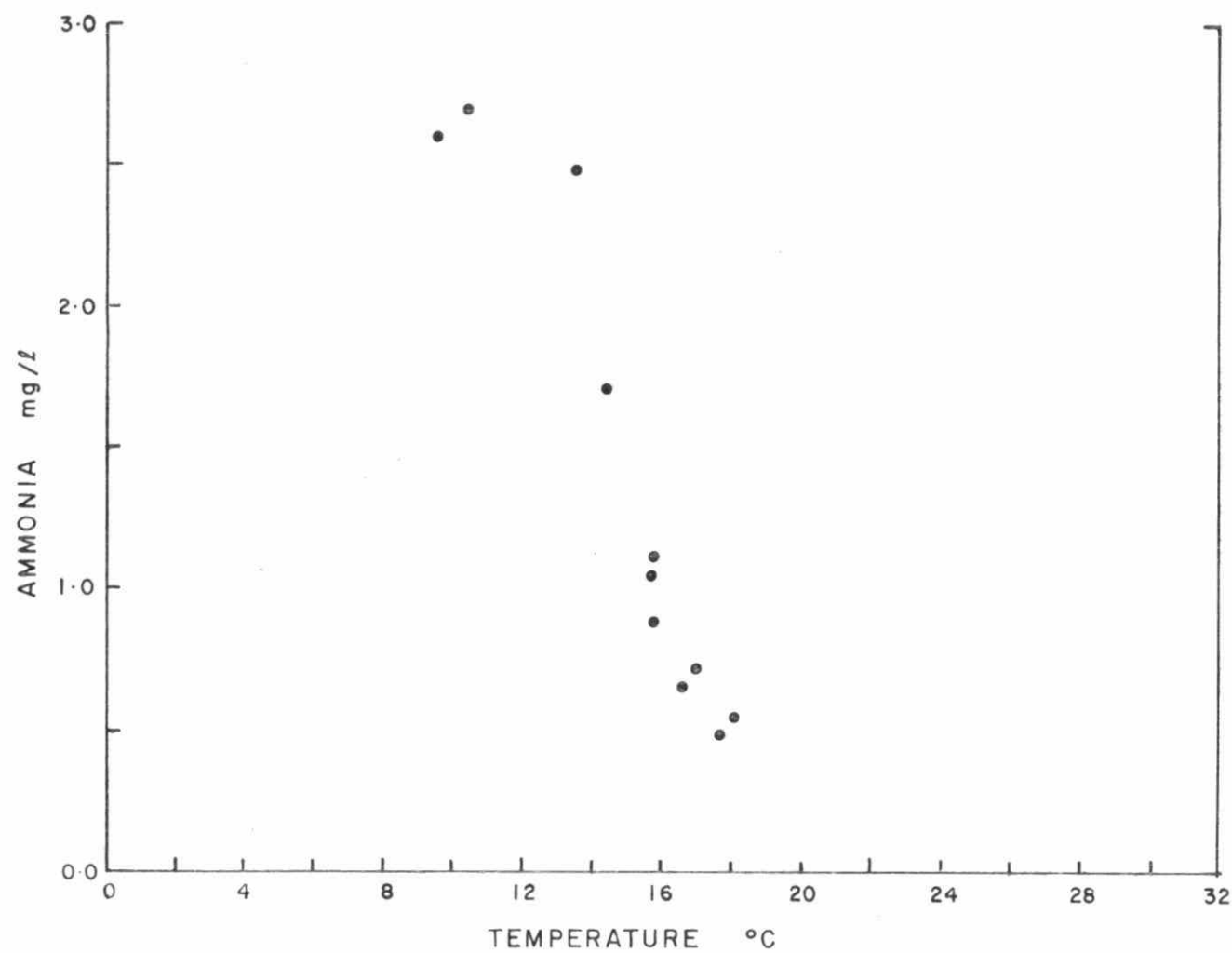
FIGURE 10 : AVERAGE AMMONIA CONTENT OF WATER COLUMN Vs AVERAGE COLUMN TEMPERATURES.
HAMILTON HARBOUR, STATION 258. 1976.
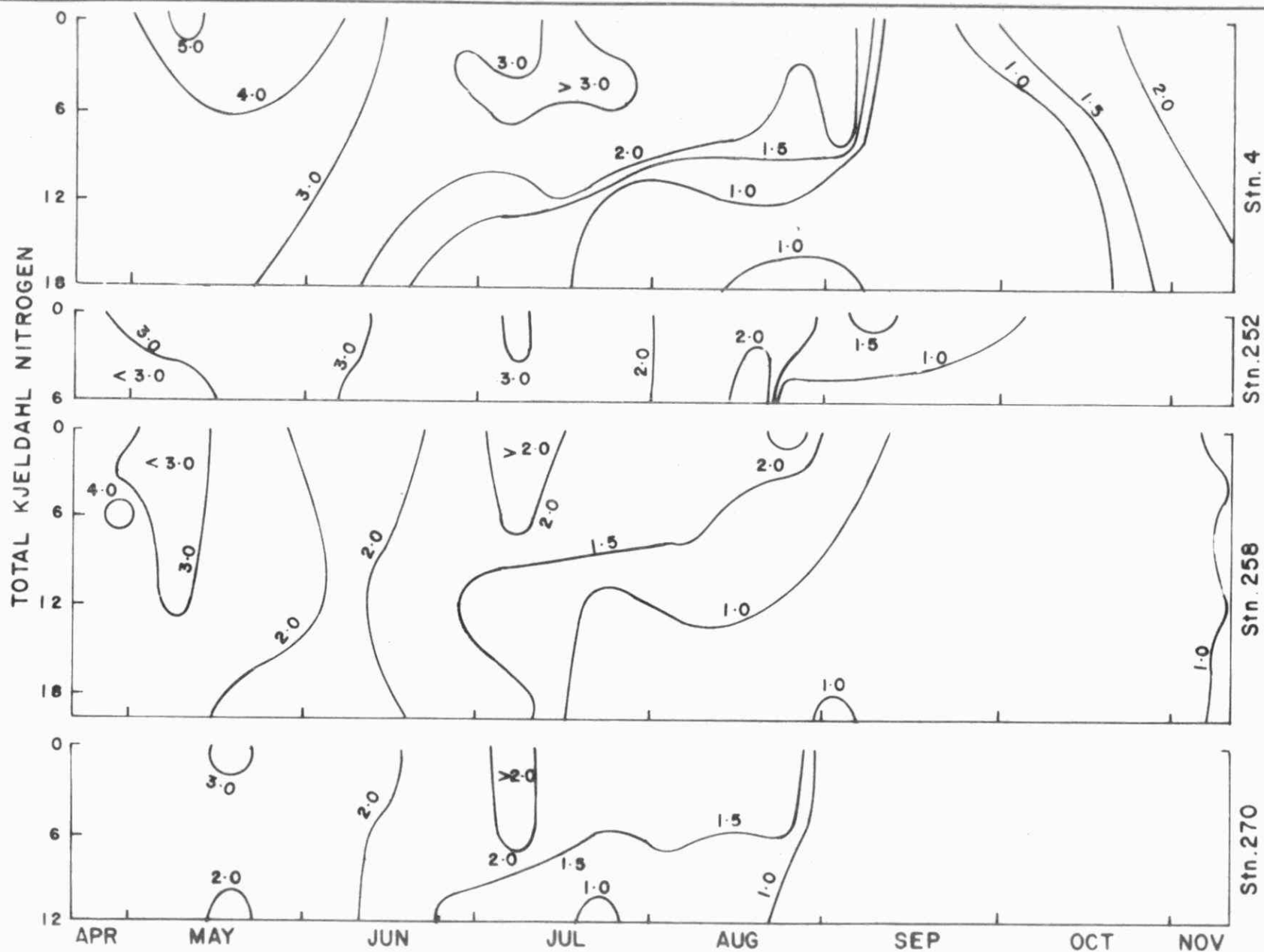
FIGURE II : ISOPLETHS OF TOTAL KJELDAHL NITROGEN (mg/l) AT MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976.

A-38
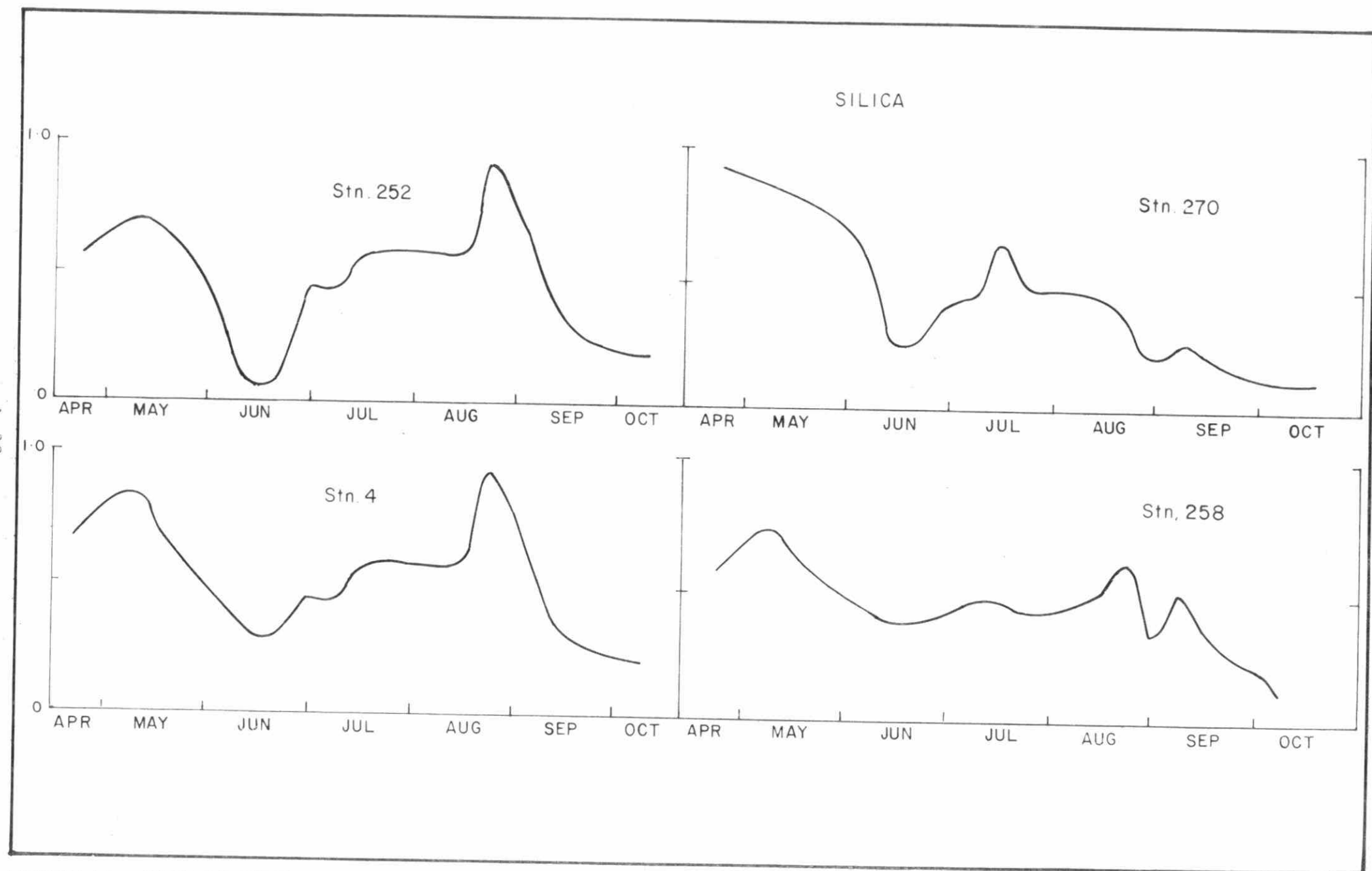
FIGURE 12 : AVERAGE WATER COLUMN CONTENT OF DISSOLVED REACTIVE SILICA AT FOUR MAJOR SAMPLING STATIONS.
HAMILTON HARBOUR 1976
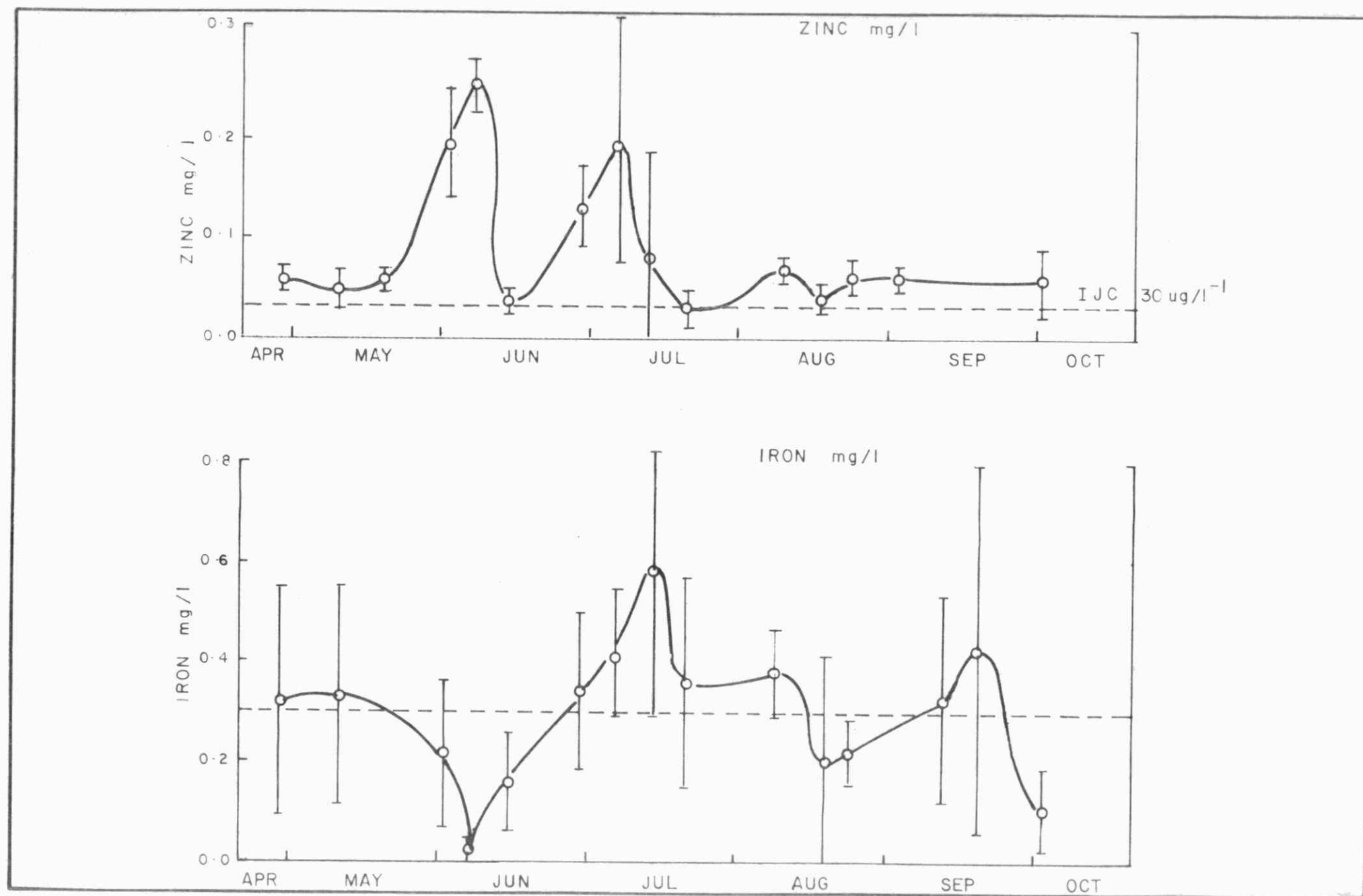
FIGURE 13 : HARBOUR MEANS ± ONE STANDARD DEVIATION OF ZINC (mg/l) AND IRON (mg/l). HAMILTON HARBOUR 1976

A-40
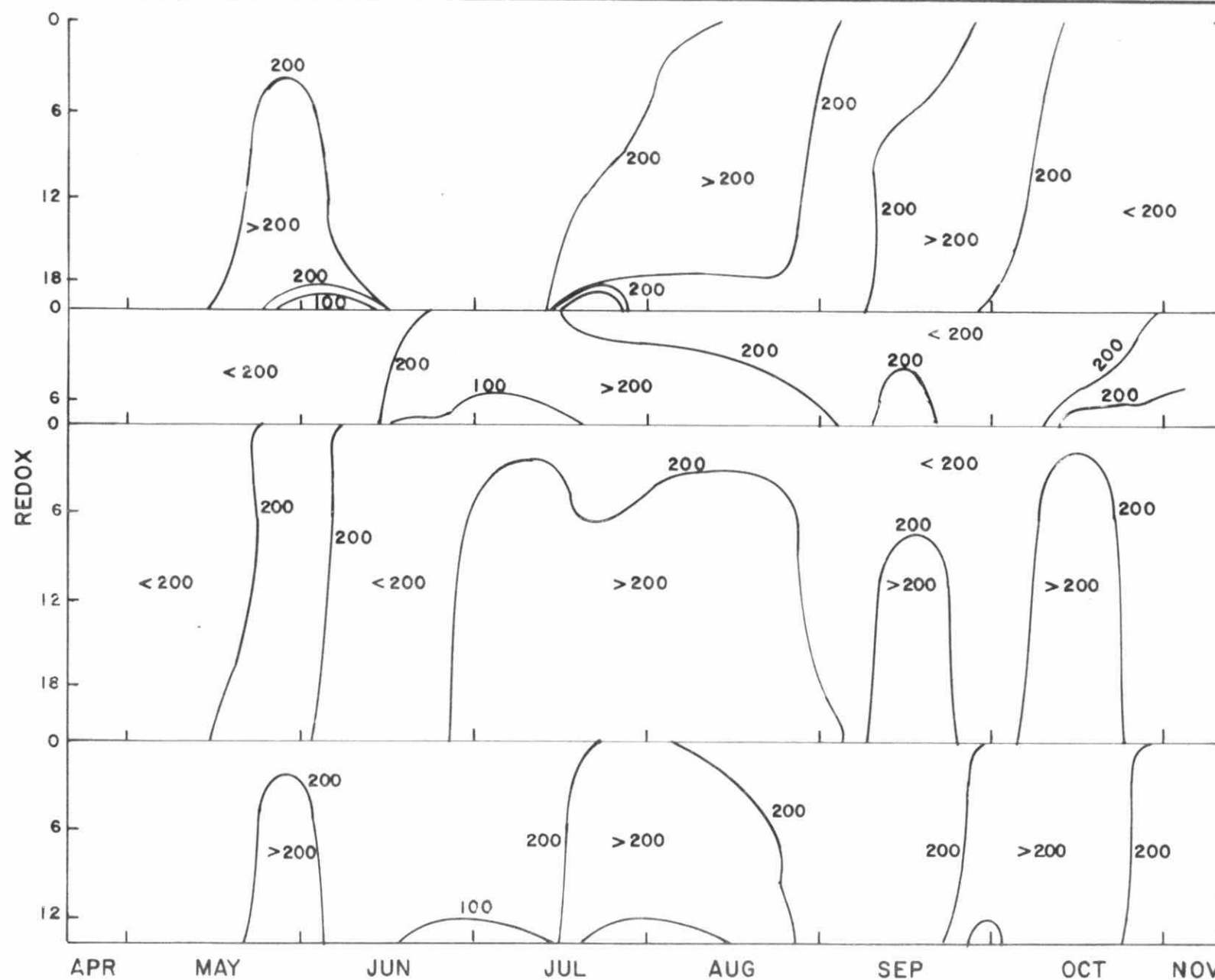
FIGURE 14: ISOPLETHS OF APPARENT REDOX POTENTIALS (mv) AT FOUR MAJOR SAMPLING STATIONS HAMILTON HARBOUR 1976

A-41
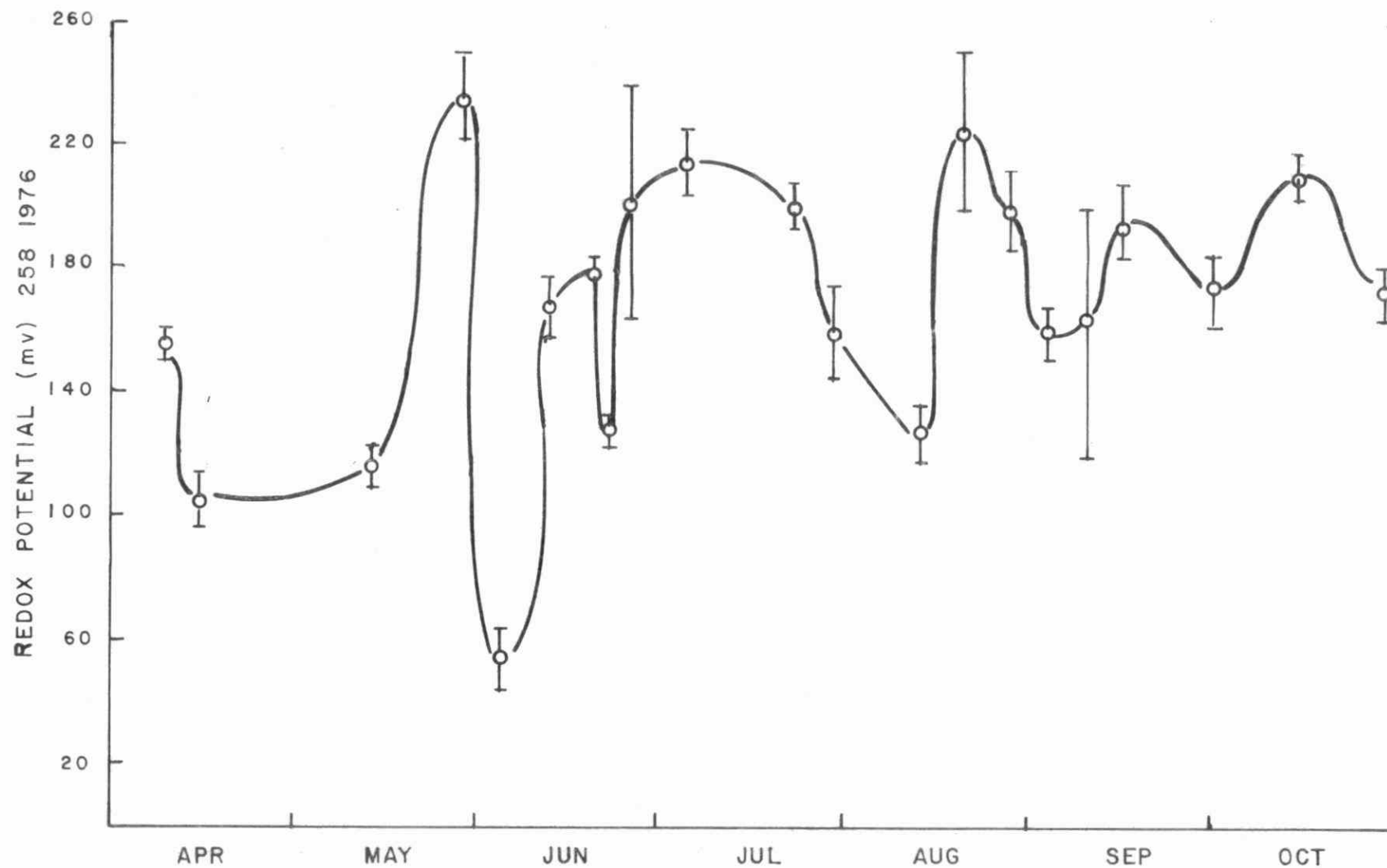
FIGURE 15 : APPARENT REDOX POTENTIAL (mv) MEANS AT STATION 258 $\pm$ ONE STANDARD DEVIATION HAMILTON HARBOUR 1976.

A-42
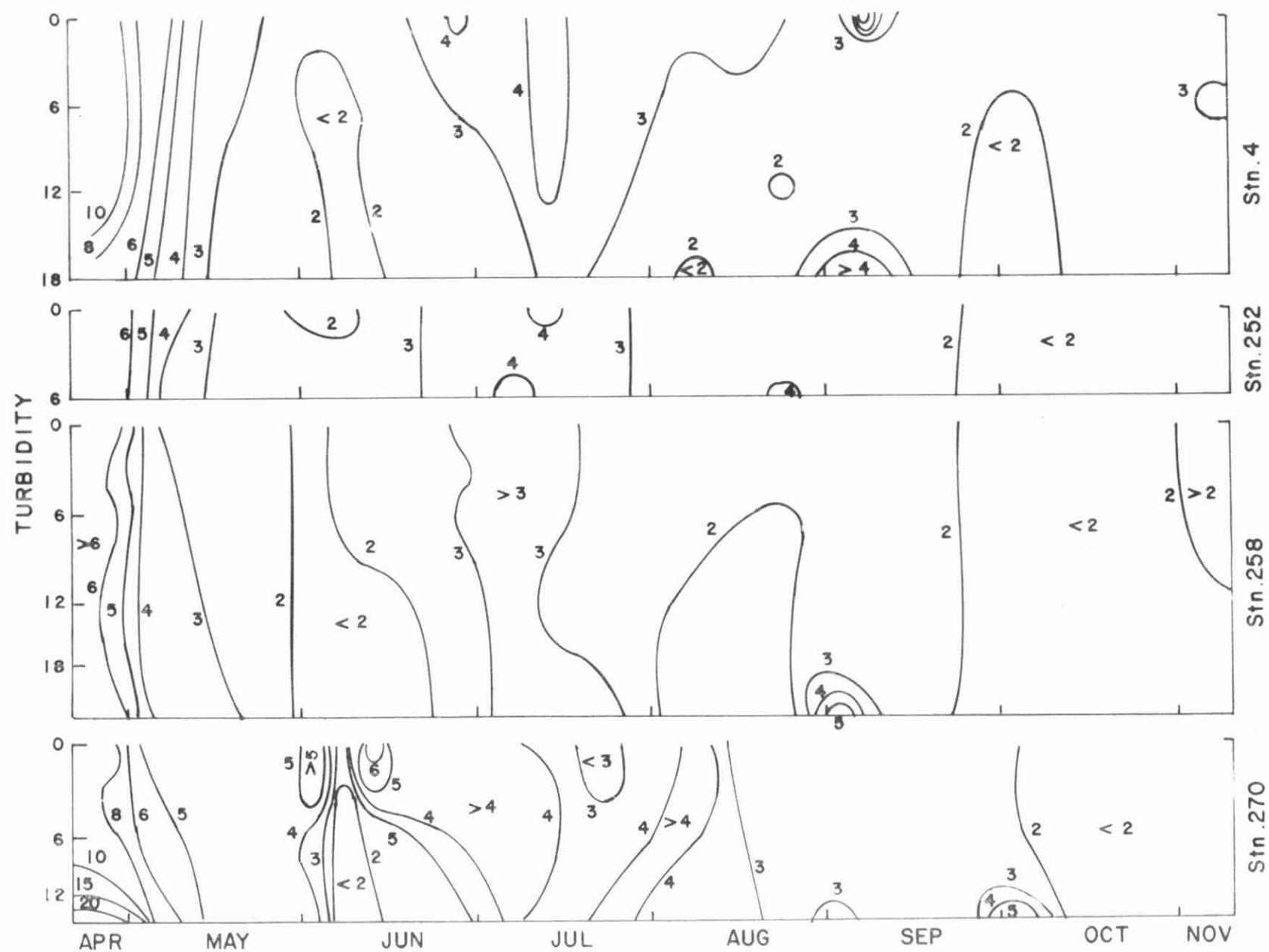
FIGURE 16 : ISOPLETHS OF TURBIDITY (F.T.U.) AT THE FOUR MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976.

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Stn. 252   0.2 m

FIGURE 17 (a) : BACTERIAL POPULATIONS OF HAMILTON HARBOUR. STATION 252.
1976.

Stn 252 0 2 m

Stn 252 6 0 m
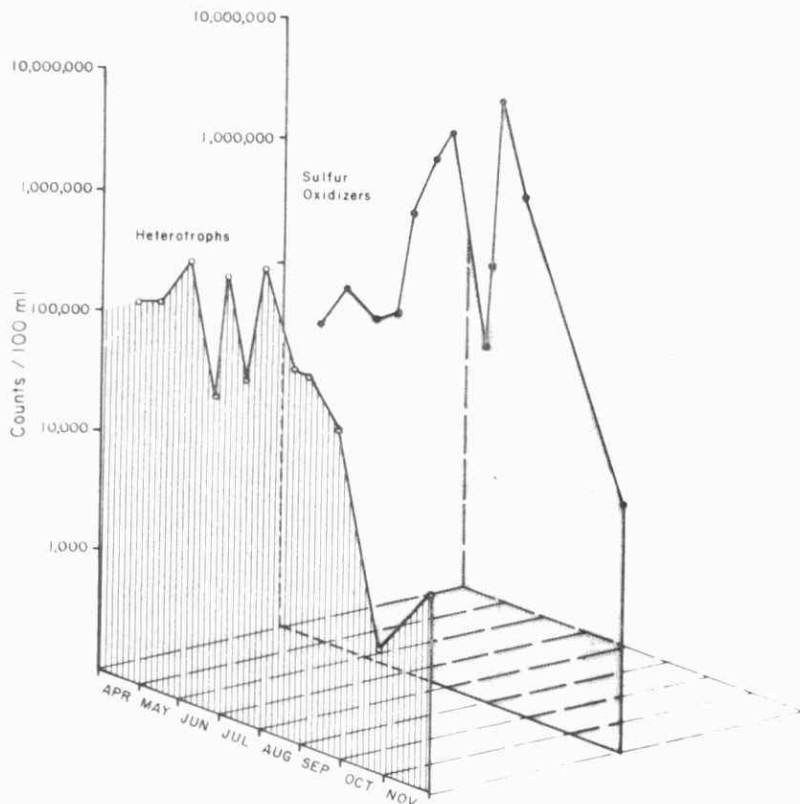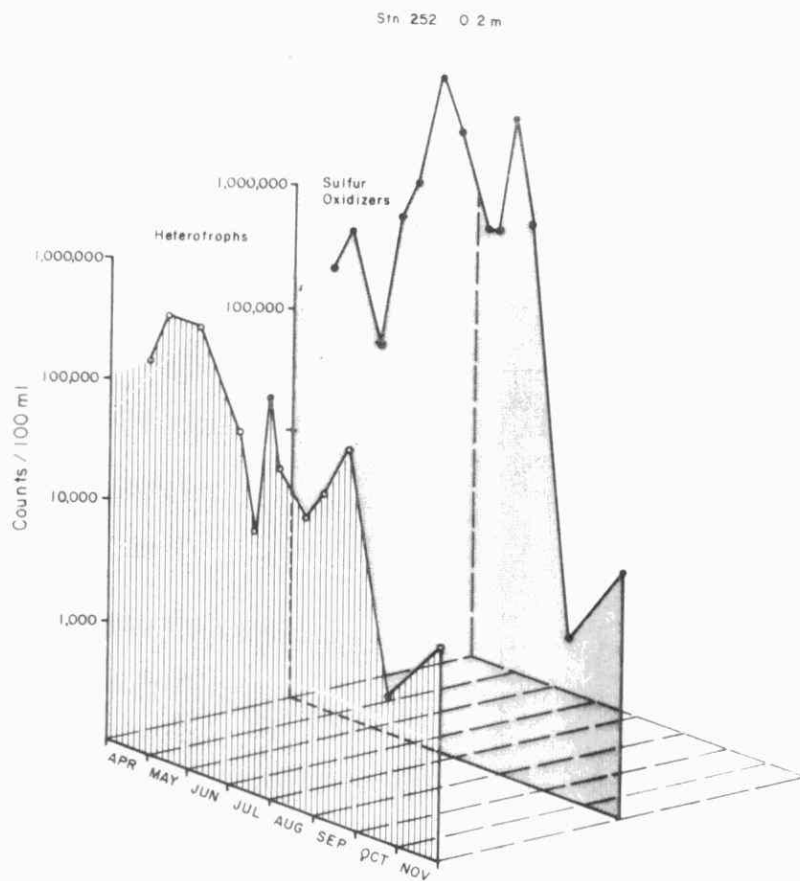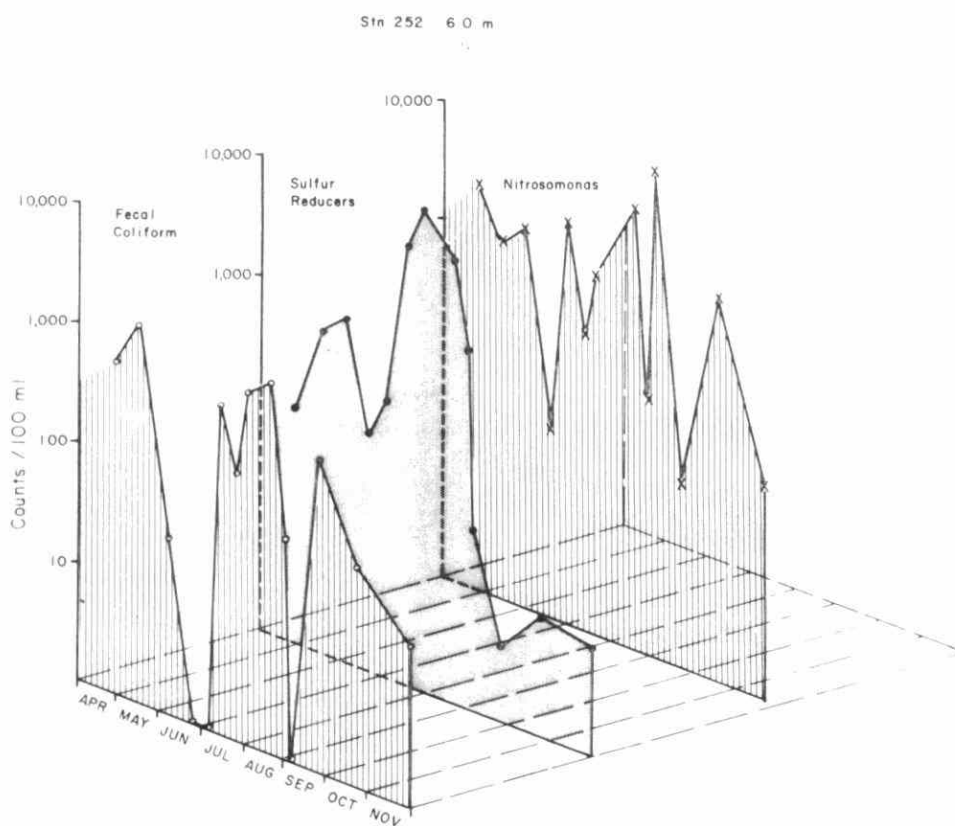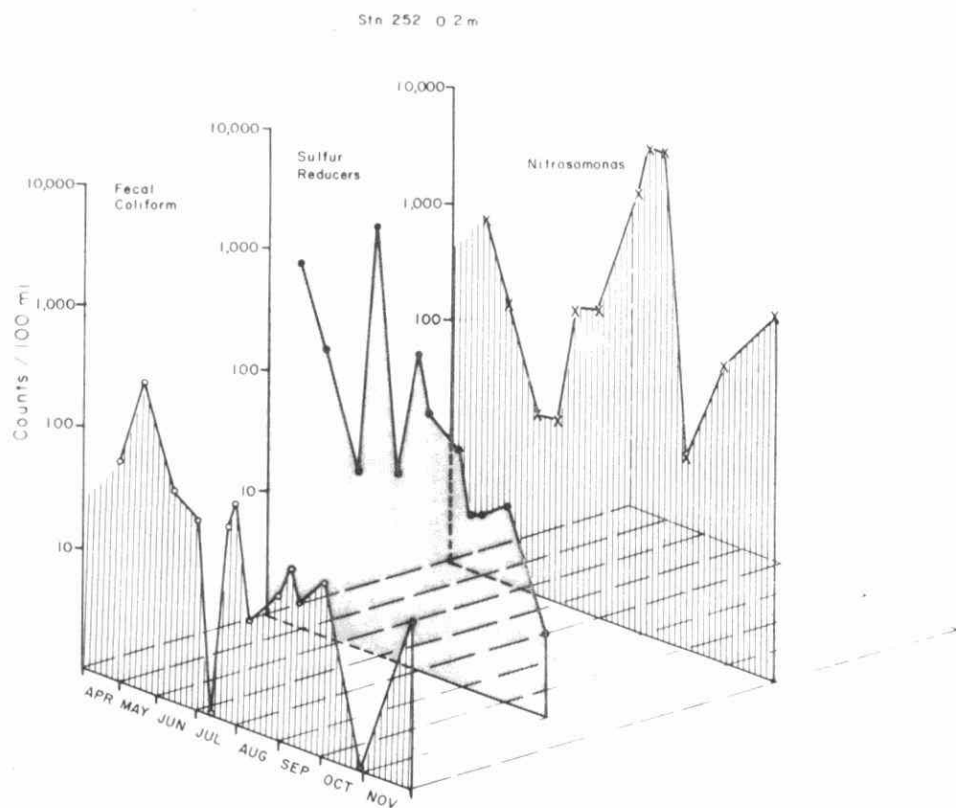
FIGURE 17 (a) : BACTERIAL POPULATIONS OF HAMILTON HARBOUR, STATION 252.
1976.
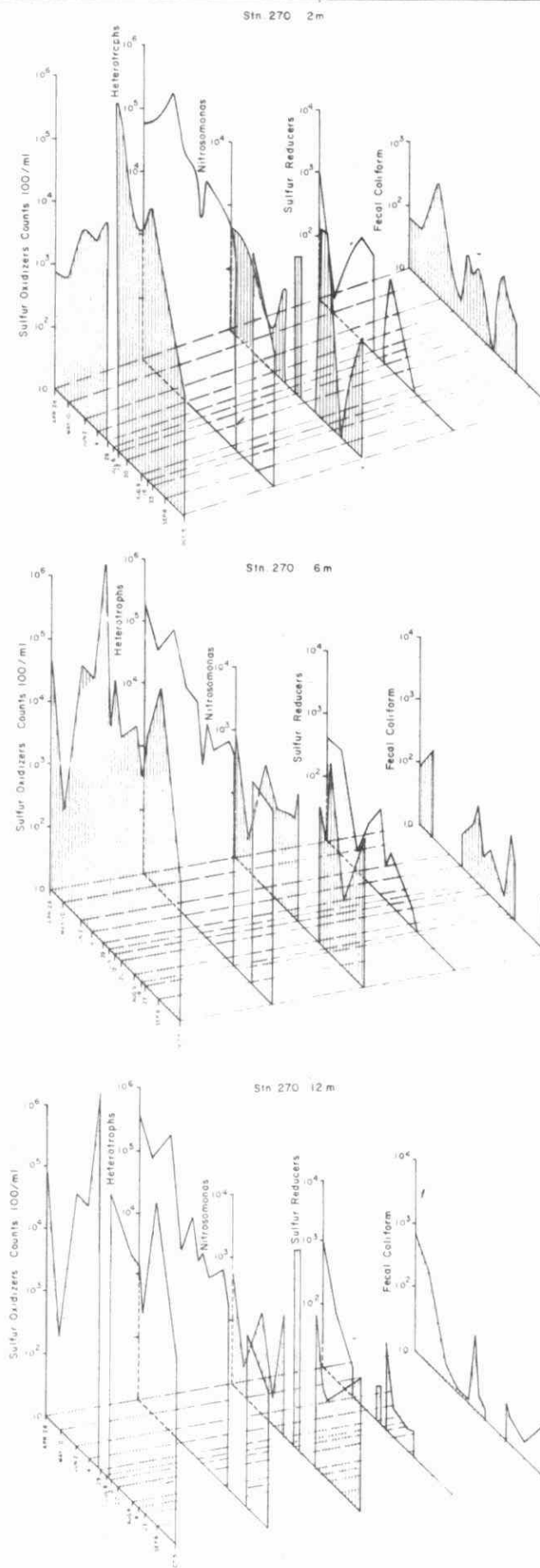
FIGURE 17 b : BACTERIAL POPULATIONS AT STATION 270 (3 DEPTHS) HAMILTON HARBOUR 1976.
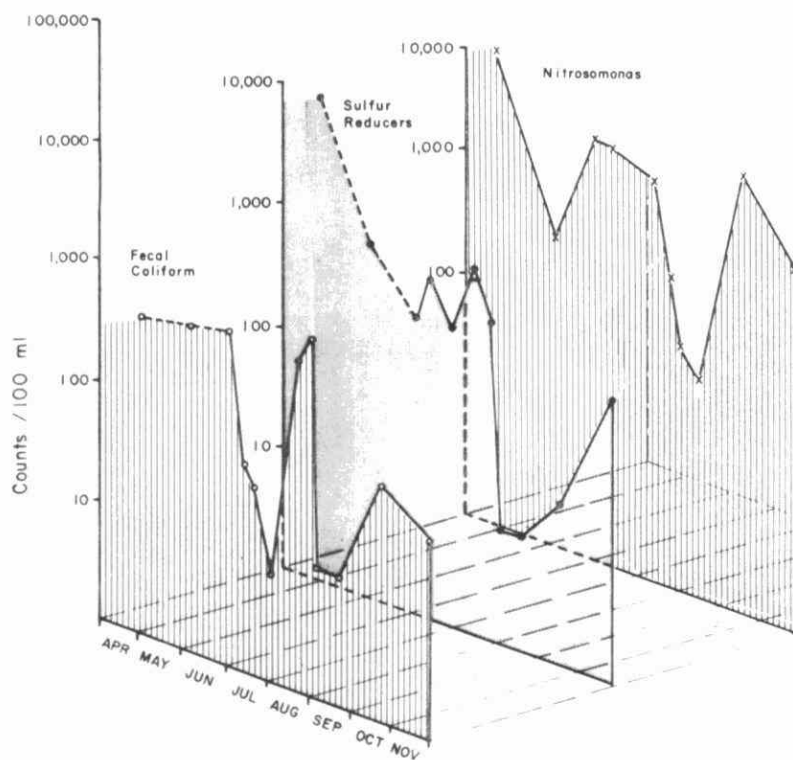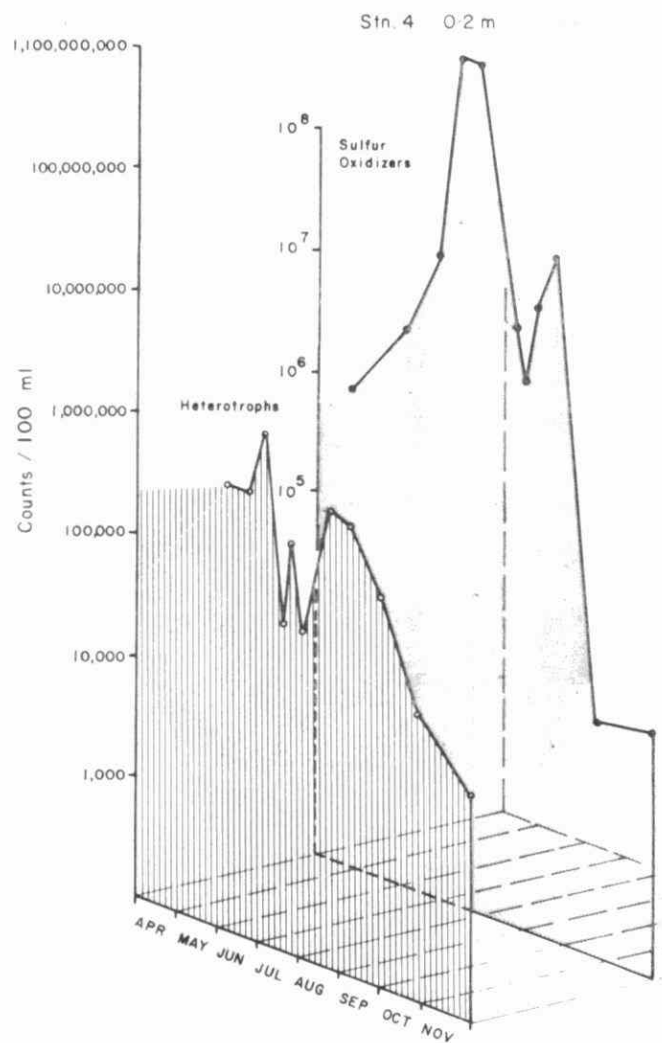
FIGURE 17 (b) : BACTERIAL POPULATIONS OF HAMILTON HARBOUR. STATION 4.1976.
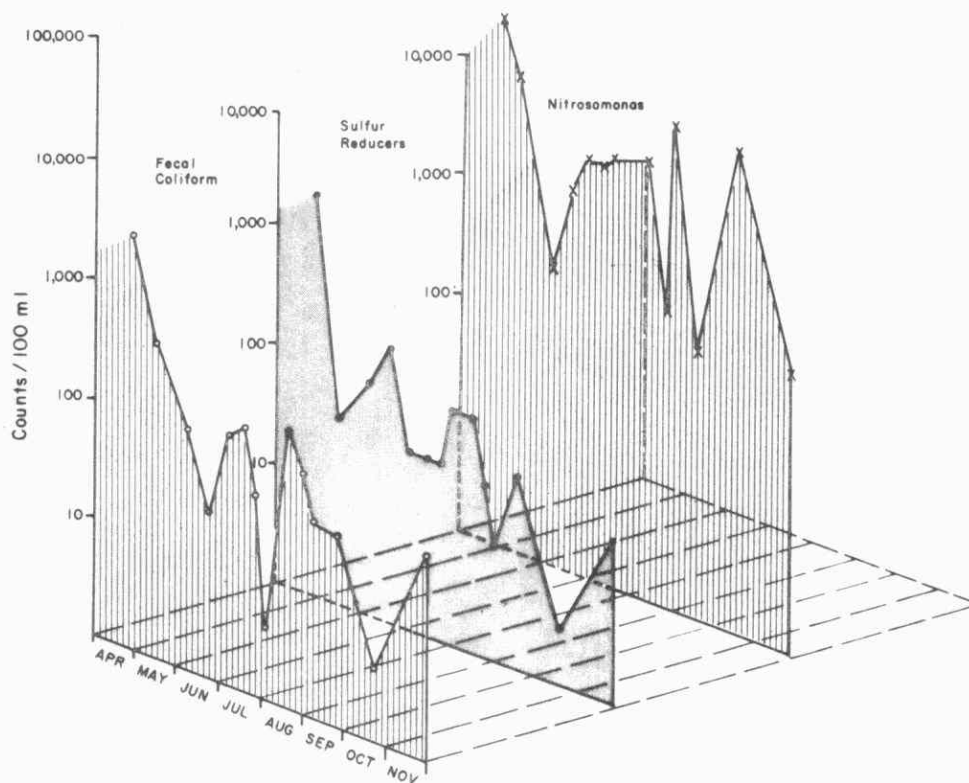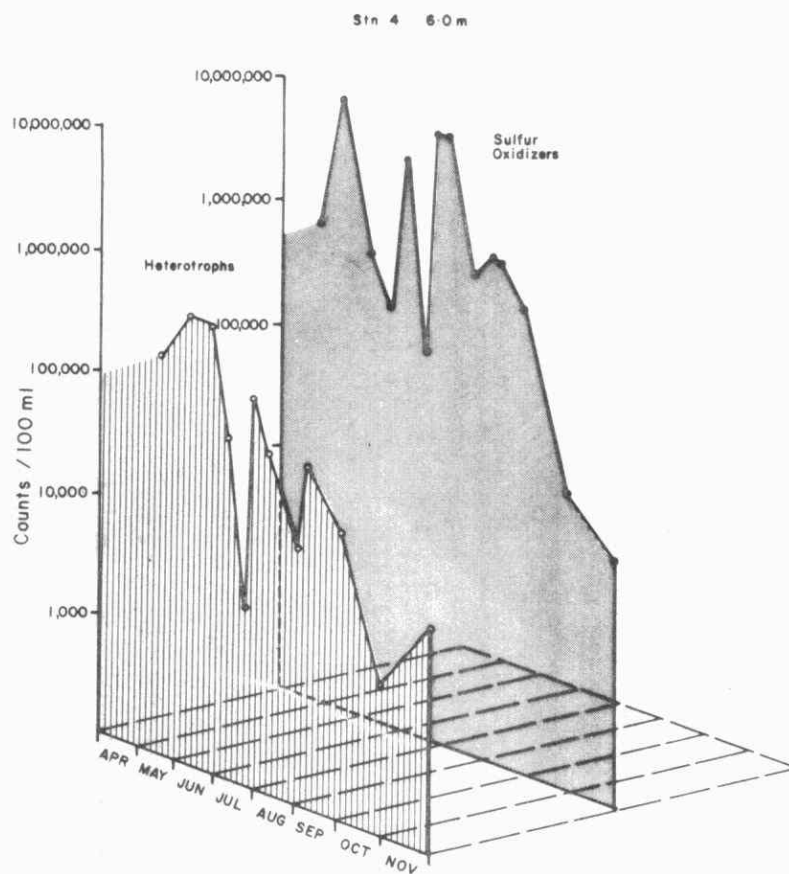
FIGURE 17 (b) : BACTERIAL POPULATIONS OF HAMILTON HARBOUR. STATION 4.1976.
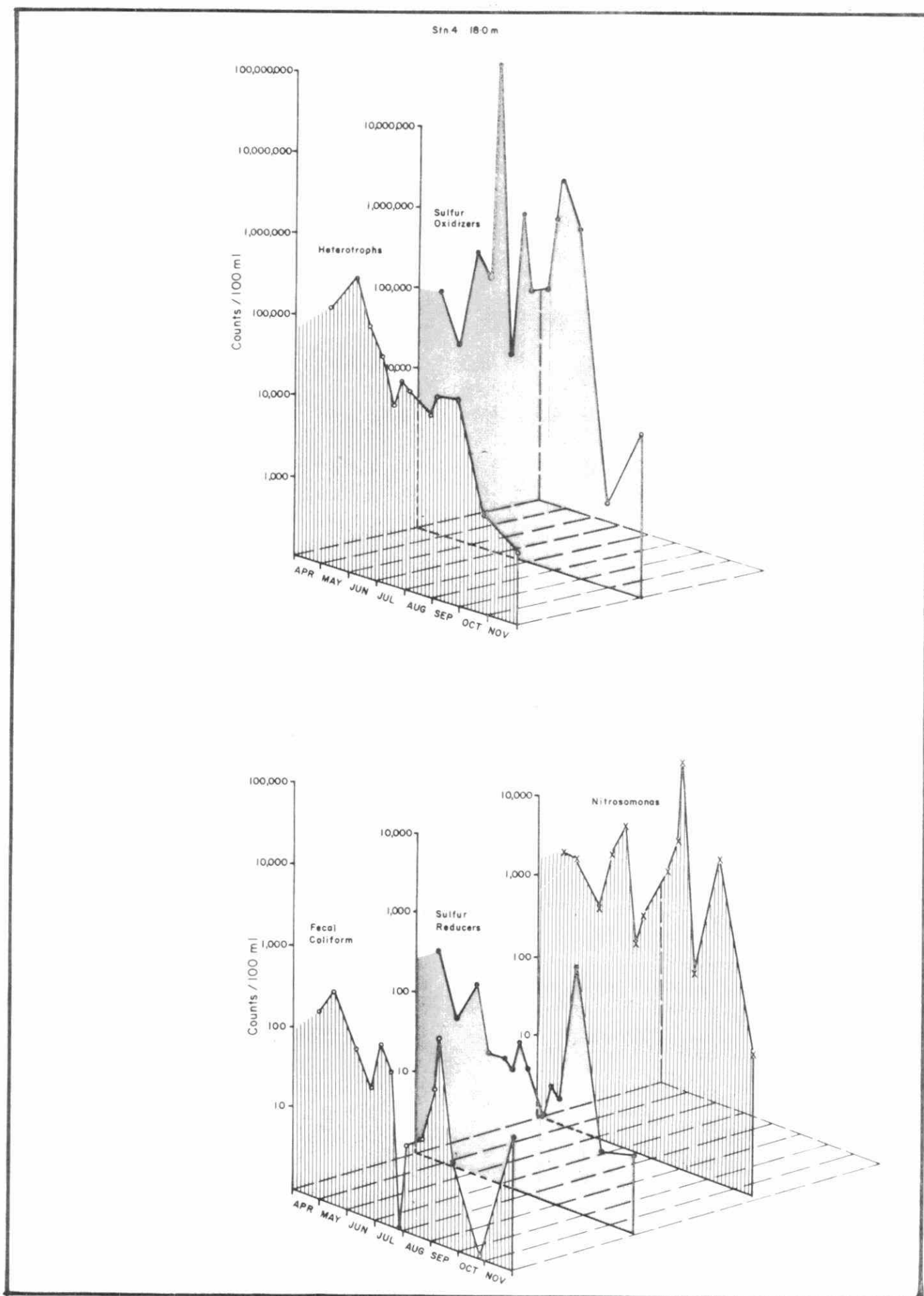
FIGURE 17 (b) : BACTERIAL POPULATIONS OF HAMILTON HARBOUR. STATION 4. 1976.
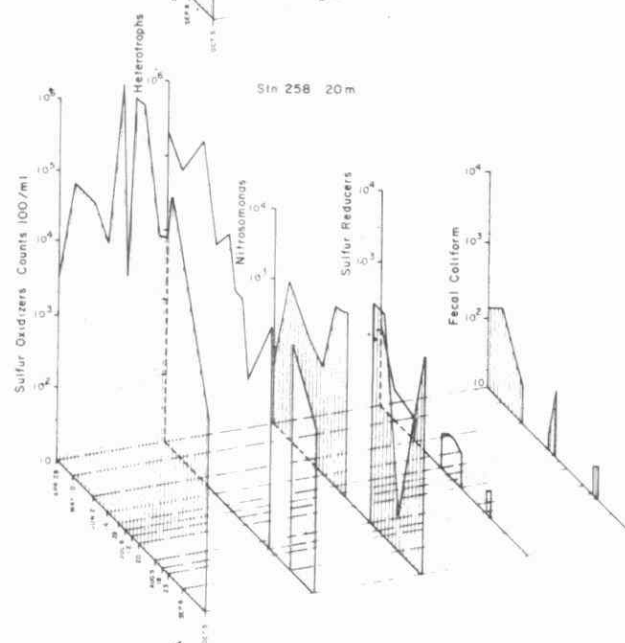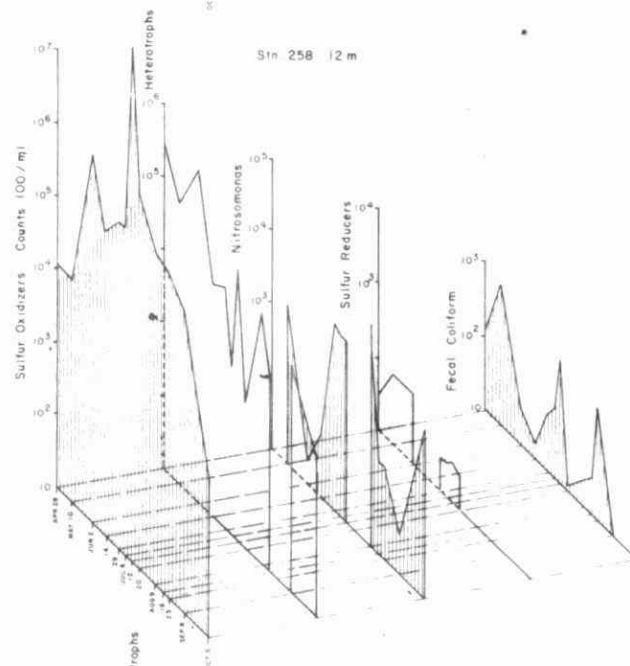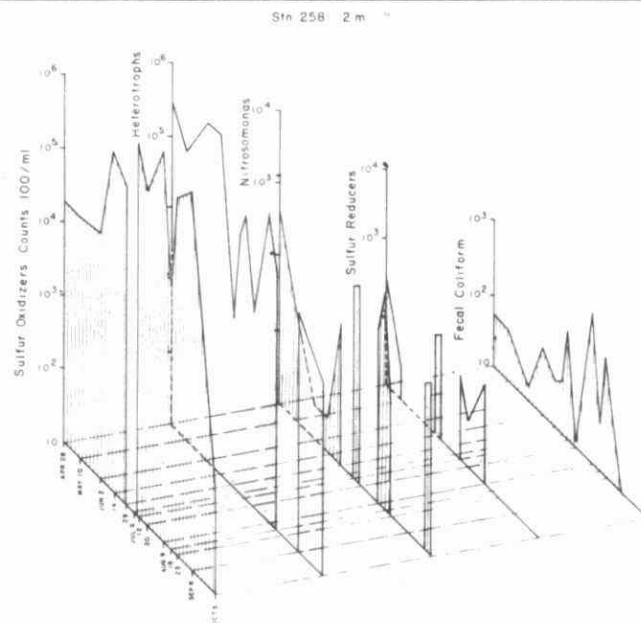
FIGURE 17 c : BACTERIAL POPULATIONS AT STATION 258 SURFACE AND BOTTOM
HAMILTON HARBOUR 1976.
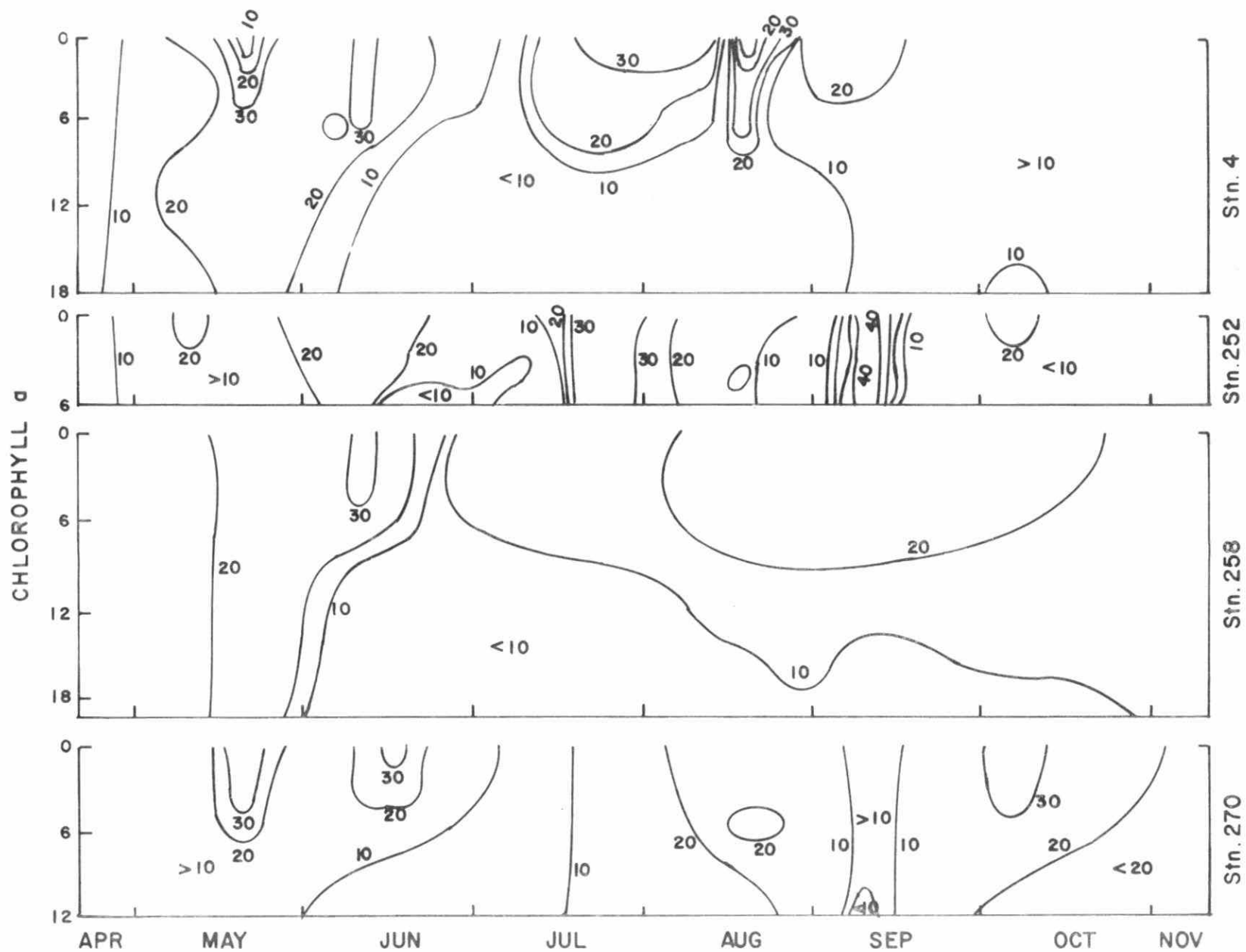
FIGURE 18 : ISOPLETHS OF CHLOROPHYLL a ug/l AT THE FOUR MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976
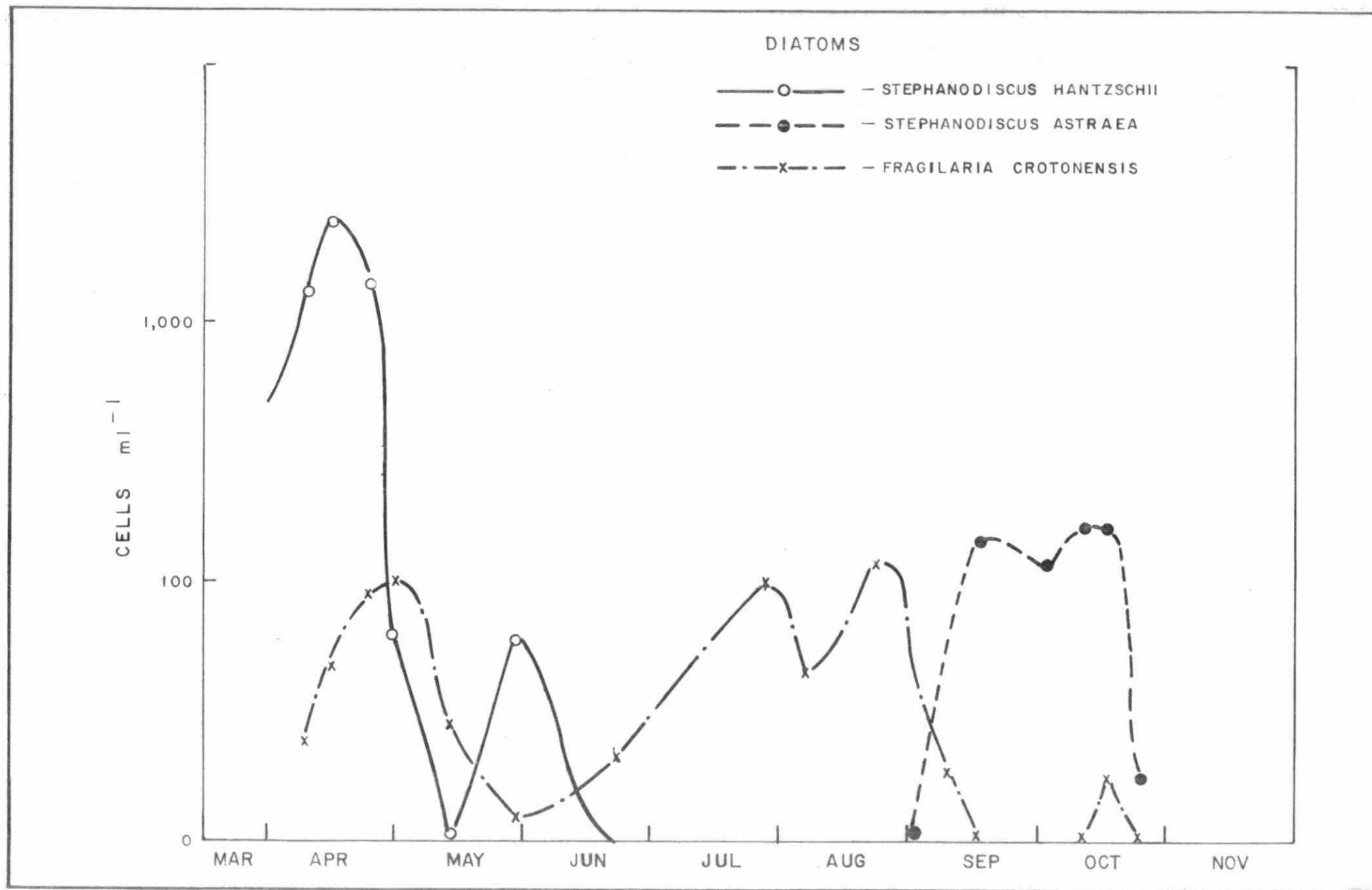
FIGURE 19 : TEMPORAL ABUNDANCE OF DIATOMS AT STATION 258. HAMILTON HARBOUR 1976 I METRE.

I Metre Depth

—o— — CRYPTOMONAS EROSA
—x— — RHODOMONAS MINUTA

FIGURE 20 : TEMPORAL ABUNDANCE OF CRYPTOPHYTES AT STATION 258, HAMILTON HARBOUR 1976 I METRE.

FIGURE 21 : TEMPORAL ABUNDANCE OF GREEN ALGAE AT STATION 258. HAMILTON HARBOUR 1976. 1 METRE.

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HAMILTON HARBOUR STUDY 1976

SECTION B

OXYGEN BUDGET OF THE HARBOUR

SUMMARY

In order to assess oxygen conditions in Hamilton Harbour,
field and laboratory studies of oxygen concentrations,
sediment oxygen demand and water column oxygen demand were
carried out in 1976. The data were used to calculate oxygen
stock of the harbour and to evaluate the contributions of
the individual processes to oxygen circulation.

Dissolved oxygen stock in the harbour shows that the harbour
water is rapidly depleted of oxygen after stratification
commences in late May or early June. The main sinks of
oxygen in the harbour are the sediment oxygen demand and
water column oxygen demand. It was confirmed that the
sediment oxygen demand depends significantly on oxygen con-
centrations in the overlaying water. More oxygen is being
depleted by sediments early in the season than in summer
when the oxygen concentrations in the hypolimnion are
already low. Most of the oxygen supplied to the harbour
is depleted in the water column (80%), lake-harbour exchange
through Burlington Channel (10%) and photosynthesis (10%).
After the initial drop of the total oxygen stock in the
harbour in early season, the oxygen stock slowly increased
throughout the summer, perhaps helped by the artificial
reaeration. To prevent the late spring oxygen depletion,
vertical transfer has to be enhanced by more efficient
reaeration. Decreases in the BOD and COD loadings to the
harbour would also decrease the water column oxygen demand
which is the major sink of oxygen in the harbour.

INTRODUCTION

Every year Hamilton Harbour (similarly to many other eutrophic
lakes) becomes low in dissolved oxygen after stratification in
late spring or early summer takes place. As the thermocline
forms, the exchange between epilimnetic and hypolimnetic layers,
being affected by the stability of the thermal gradients,
is decreased and the hypolimnion becomes anoxic within two
or three weeks. As Hamilton Harbour is characterized as
being vertically unstable, the large oxygen depletion is also
evident in the epilimnion. Many chemical, physical and
biological processes are involved in the consumption, produc-
tion and exchange of oxygen within the harbour and its
environment. Oxygen is depleted in the water column and by
the bottom sediments. Oxygen is supplied by exchange between
the atmosphere and the water surface, photosynthesis and the
inflow of well-aerated Lake Ontario water (Palmer and Poulton,
1976). With respect to the total budget, changes in the
dissolved oxygen stock have to be considered with regard
to these sources and sinks.

Two of the most important processes of oxygen depletion,
i.e. water column oxygen demand and sediment oxygen demand,
have been extensively studied in other bodies of water
(Mortimer, 1941, 1942). The relative importance of these
two processes varies in different water bodies. Hutchinson
(1957) calculated that oxygen demand in the water column
of some lakes was sufficient to consume all hypolimnetic
oxygen. In other cases, oxygen consumption by the sediment
could account for all oxygen loss (Hargrave, 1972a). Generally
both water column oxygen demand and sediment oxygen demand
are important, ad their relative significance is a function
of the reservoir size and depth as well as the water and
sediment quality. Techniques used for measuring oxygen
demand are described in the literature (Lucas and Thomas 1971;
Smith and Teal 1973; James 1974; Rolley and Owens 1967;
Hargrave 1969a; Martin and Bella 1971; Pamatmat 1971; and
Edberg and Hofsten 1973).

The biological and chemical oxygen demands of sediment are
not really separable because of the "working" of the sediments
by organisms such as oligochaetes. This movement results in
increased chemical oxygen demand as the vertical flux of
oxygen in upper layers is increased. Respiration by these
benthic organisms has not been given attention it deserves,
although Hunter et al (1973) made some preliminary observations
on the subject. To date, it is not possible to generalize on
the effects of benthic organisms on sediment oxygen consumption.

Several authors have used formalin and/or antibiotics to
separate pure chemical and biological uptakes. Hargrave
(1969b) used antibiotics to eliminate bacterial action and
found that bacterial uptake contributed 30-45% of the
total oxygen uptake in Lake Marion in British Columbia.
The actual value was dependent on the time of the year and the
bacterial population present. Some authors used 1-2%
formalin solutions to separate the chemical oxygen demand
from the community respiration. Establishing what part of
the uptake is chemical and what is biological in nature
is difficult as the ratio varies with time, space and
sampling method.

Hargrave (1972a) reported that sediments (undistributed cores)
collected in Lake Esrom, Denmark, had chemical uptakes
measured in the laboratory between 10-30% of the total
uptake. For sediments taken from different sections
of the core collected in the same lake mixed in oxygenated
water in the laboratory it was found (Hargrave, 1972c) that
chemical uptakes accounted for 30-60 % of the total.
Pamatmat (1971) using formalin poisoning of marine sediments,
found chemical contributions of 31-100% of the total oxygen
uptake. For similar conditions, Smith and Teal (1973) found
much lower in situ values of total oxygen uptakes at a
depth of 1850 m with negligible chemical uptakes. Smith
(1974) used both formalin and antibiotics to separate total
sediment oxygen demand into chemical, total biological and

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and bacteriological uptakes of deep-sea sediments. The mean of 20 stations illustrated that chemical demand accounted for 45.4%, while bacterial respiration formed 8.8% of the total.

Owens (1964) presented a view of the main sources of oxygen in the Thames estuary. Atmospheric reaeration contributed nearly 70% of the total, with tributaries, ocean exchange and photosynthesis contributing approximately 9% each. The remainder was supplied by reduction of nitrates and sulphates and by rainfall. Difficulty in determining the atmospheric reaeration rates were pointed out and it was estimated that, in the mean, 6 g m^{-2} d^{-1} of oxygen was being supplied to the estuary from the atmosphere.

Lasenby (1975) studied oxygen deficit in 14 southern Ontario lakes. He calculated relative consumption of oxygen by the sediments and the water column of Dickey Lake using fixed values of oxygen uptakes. In the mean, for this lake, 27% of oxygen was consumed by the sediment. Despite the number of articles on the mechanism of oxygen uptake there have been few attempts to assimilate these mechanisms to form an oxygen budget.

Hypolimnetic oxygen depletion in central and eastern basins of lake Erie was studied by Burns (1976). For precise calculations of hypolimnetic oxygen budget, the vertical exchange between epilimnion and hypolimnion was considered. Vertical mass transport of oxygen for Lake Erie was estimated from the heat budget of the lake. In the mean, about 19% of the oxygen depletion in the hypolimnion was replaced by the exchange mechanism.

In previous Hamilton Harbour reports (MOE, 1975, MOE, 1977) oxygen contents of the harbour were calculated from the available vertical oxygen profiles, and oxygen budgets were estimated using literature data on sediment oxygen demand. Since experimental data are preferable, sediment

oxygen demand and water column oxygen demand were measured
in 1976 by in situ methods and used for the budget of the
harbour.

Sampling stations employed in this work are depicted in
Figure 1. Once a week depth profiles were obtained at 1 m
intervals of dissolved oxygen, conductivity, temperature,
pH and redox potential at the four major sampling stations.
Harbour depth profiles were determined monthly at 19 stations
located throughout the harbour. Volume samples were collected
weekly and analysed for chlorophyll a and alkalinity. Samples
for nutrient analysis were foraen, and samples for chlorophyll
a were preserved with $MgCO_3$. Light and dark bottle experiments
were performed to determine the significance of photosynthesis
as an oxygen source in Hamilton Harbour. COD and BOD_5
determinations were made throughout the year using procedures
described in Standard Methods (1971).

METHODS

Sediment Oxygen Demand - In Situ Measurements

A measuring chamber for sediment oxygen demand, made of
clear, 3mm thick plexiglass was equipped with flanges to
prevent it from sinking into the mud. The exposed area of
the sediments was 0.4 m^2, and the box contained 0.2 m^3 of
water. As all measurements were carried out at a depth well
below the photic zone (as determined experimentally using
submersible photocells) no blackening of the box sides was
necessary. The sonde of the water quality meter was secured
inside the chamber and the surface unit on board an anchored
boat scanned and recorded 6 parameters (dissolved oxygen,
pH, conductivity, temperature, redox potential and depth).
The box was lowered slowly to the bottom to minimize lifting
of the mud particles. During the descent of the box,
partial mixing of the top water initially in the box, and
deeper waters took place. This mixing and possibly a small
amount of lifted mud caused an initial (30 min) surge in the
recorded dissolved oxygen concentration. The only stirring
inside the box was by a magnetic stirrer near the dissolved
oxygen probe. Dye experiments to test the efficiency of
mixing in the chamber determined that complete mixing was
achieved within four minutes from the inoculation of the
dye. The dissolved oxygen meter was calibrated before each
run against a Winkler titration with an accuracy of 0.1
mg/l, and could be read with a precision of 0.01 mg/l.
After the 30 min stabilization period, the dissolved oxygen
concentration was recorded every five minutes. The rates of
change of the oxygen concentration inside the box varied
from 0.05 to 0.3 mg l^{-1} h^{-1}. After about 4 hours the run
was discontinued and the box lifted. During the longer runs
(up to 44h) the system was set to work in an automatic mode
scanning the parameters every 20 min.

The change of the oxygen concentration inside the box was caused by sediment oxygen demand as well as by the oxygen demand of the enclosed water. This change can be expressed as

$$\frac{\Delta c}{\Delta t} = \frac{A}{24V} k_s + \frac{1}{24} k_w \qquad \dots (1)$$

where k_s is the sediment oxygen demand $g\ O_2\ m^{-2}d^{-1}$, k_w is the water column oxygen demand in $g\ O_2\ m^{-3}d^{-1}$, V is the volume of the chamber in m^3, A is the exposed sediment area in m^2 and $\Delta c/\Delta t$ is the change of oxygen concentration in the box per hour ($mg\ l^{-1}\ h^{-1}$). The larger the ratio A/V is, the smaller is the relative contribution of the water column demand. A relatively low ratio in our case was dictated by the use of proportionally large multiprobe sonde. Water column oxygen demand was evaluated in separate runs and was used in equation (1) to calculate k_s.

Sediment Oxygen Demand - Laboratory Measurements

A sample of bottom sediments near station 270 was collected with an Ekman dredge and refrigerated. Sediment oxygen demand was measured in a simple cell shown in Figure 2. Clear plastic tube with an ID of 8.7 cm and total length of 40 cm was equipped with a probe of YSI, Model 57 dissolved oxygen meter and a stirrer. The tube was wrapped in black plastic tape to prevent photosynthesis. About 3 cm of the sediment was placed on the bottom of the tube which was filled with distilled water and left undisturbed for at least 48 hours to settle the mud particles and compact the sediment surface. The whole tube was submerged in a constant-temperature water bath maintained within $0.1^{O}C$ of the experimental temperature. Thickness of the sediment layer was found not to affect the results (layers always over 2 cm). After 48 hours or more, water in the tube was replaced with well oxygenated distilled water, carefully avoiding introduction of bubbles. The recording meter was

turned on and the slow decrease of oxygen concentration
was monitored and recorded on a strip chart. The run at
every temperature level was repeated, starting at different
oxygen concentrations. It was found that time-oxygen con-
centration curves are well reproducible. Experiments were
also repeated with good reproducibility after the sediment
layer in the cell was exchanged and allowed to settle.
SEdiment oxygen demand was measured at three different
temperatures, i.e. $25^{\circ}C$, $17.2^{\circ}C$ and $11^{\circ}C$. To investigate
the relation between the chemical and biological sediment
oxygen demand, a 4% solution of formalin was used in some
of the runs.

Water Column Oxygen Demand and Harbour Oxygen Stocks

On two in situ studies, the chamber that was used for determination
of the sediment oxygen demand was separated from the sediments
by a sheet of 3mm thick plexiglass with the same measuring
procedure previously described. Other water column oxygen
demand data were obtained by the dark bottle method. Ten
500-ml bottles were painted black, filled with water samples
collected at different depths and placed into the harbour
for 24 hours. The bottles were moored at the same depths as
the water samples were taken from. The initial and final
dissolved oxygen concentrations were determined by Winkler
titration. Results of the 24-hour incubation were compared
to the three hour light and dark bottle studies. Long term
(>4 hours) studies using the dark bottle technique can give
spurious results as the bacterial flora can change from its
original composition and abundance, and wall effects can
become pronounced. Data from such an experimental design
would possibly deviate from the actual water column demand.

Vertical profiles of dissolved oxygen were used to calculate
an oxygen budget using a modified method of Boyce (1973).
The harbour was divided into 500 x 500 m cells, and each
cell was assumed to have a flat bottom with an appropriate

mean depth. The water volume and the volume content of the
harbour were then calculated in 1 m layers. In each layer,
only the cells with the total depth larger than that of the
layer were counted. The mean oxygen concentration in each
cell was determined by integration of the dissolved oxygen-
depth profile at the station closest to the cell, assuming
linear concentration changes between the individual depth-
oxygen points.

RESULTS AND DISCUSSION

Temperature vs depth and dissolved oxygen vs depth profiles
from the centre of the Harbour (Station 258) in 1976 are
illustrated in Figures 3a and 3b. From the temperature
profiles it was evident that the harbour was thermally
unstable throughout the summer period. Similarly, the
dissolved oxygen profiles changed considerably from week to
week suggesting large vertical transfer of oxygen through
the water column. These transfers were not entirely dependent
on wind conditions as mass exchange and shipping could alter
the thermal profiles as well.

All dissolved oxygen profiles, available for 1972, 1975 and
1976 were used to calculate dissolved oxygen contents
(stocks) of Hamilton Harbour. The calculated stocks are
illustrated in Figure 3. Rapid decreases of oxygen content
were apparent during the late spring of all three years. In
1976 total stock of oxygen decreased from 2.87×10^6 kg near
the end of May to 0.81×10^6 kg in mid-June. There was
partial recovery in stock levels during the middle of 1976.
This may be in part a result of artificial mixing using air
diffusers (Section, Artificial Mixing).

Mean oxygen concentrations in the harbour water in the top
layer (0 to 3m below surface) and bottom layer (7m to bottom)
in 1976 were calculated from the oxygen content values and
are shown in Figure 4. Oxygen concentrations of the bottom

layer (shown as a full line) decreased rapidly after mid-May
with the lowest mean concentration of 0.4 mg l^{-1} recorded on
June 18, 1976. Oxygen concentrations in the top layer are
shown as a broken line. The dotted line connects the
calculated epilimnion saturated concentrations, determined
from the temperature measurements. It is evident that even
the epilimnion becomes undersaturated during the summer due
to the rapid uptake of oxygen in the water mass and the
vertical flux between the layers.

Sediment Oxygen Demand - Field Data

The results of the individual runs to determine sediment oxygen
demands are shown in Table 1. Most of the studies lasted 4
hours. All measurements were carried out at Station 270
(Figure 1) at a depth of 13.5 m except on May 10 and May 14
when measurements were made at Station 252 (8m depth).
Station 270, although of moderate depth was representative
of the rich organic sediments of the harbour. The high
organic content of the sediments at Station 270 is characterized
by loss on ignition values of 9.3% and chemical oxygen
demands of 120 mg/g (Section C , Water Chemistry). The
organic content of sediments from 16 other locations throughout
the harbour varied considerably but the mean approached the
Station 270 value. Station 252 had less than one half of
the organic content found at Station 270, but as sediment
oxygen demand results are primarily the function of oxygen
transfer (unless the organic content is very low) the
differences in the organic content did not affect the rates
of oxygen consumption significantly (cf. Table 1 and Figure
5).

Temperatures of the different studies varied from 11 to $16^{o}C$
and no attempt was made to introduce temperature compensa-
tion as this added little variation to the results. Sediment
oxygen demand revealed a strong correlation with the mean
oxygen concentration in the measuring chamber (Correlation

coefficient $r = 0.982$ is significant at 99.9% level). This dependence of measured sediment oxygen demand k_s on dissolved oxygen concentration c is illustrated in Figure 6, and the correlation line can be expressed by the equation:

$$k_s = 0.72 + 0.26c \qquad \dots (2)$$

where k_s is in g $O_2 m^{-2} d^{-1}$ and c is in mg l^{-1}. A dependence of the sediment oxygen demand on oxygen concentration has been previously reported by Hargrave (1969a), Edwards and Rolley (1965), and Edberg and Hofsten (1973). Other authors, however, have claimed no oxygen concentration dependence of the rate (Martin and Bella, 1971) or at least not for concentrations above 6 mg l^{-1} (Hargrave, 1969a). Some data from the literature on oxygen uptakes of sediments affected by eutrophication are also shown in Figure 6.

Two important aspects of the concentration dependence of sediment oxygen demand are suggested by the relationship of the two parameters. The first is the near linear characteristics of the dependence. Short term studies indicated that the rate was constant over confined periods of time. The actual dependence, however is probably somewhat curved as evident from the 44 hour run, results of which are illustrated in Figure 6. Chemical oxygen demand and short term biological demands could be linear, but biological demands are altered when low oxygen concentrations are reached.

The second important aspect depicted in Figure 6 is that the sediment oxygen demand did not apparently fall directly to 0 as the oxygen concentration decreased. This was confirmed by long term runs. There is evidence that the sediment oxygen demand is falling rapidly at oxygen concentrations below 0.05 mg l^{-1}. For practical purposes, however, the dependence of the sediment oxygen demand on oxygen concentration can be approximated by a straight line with a positive intercept at zero oxygen concentration.

The biological components of the oxygen demand can be deter-
mined by use of toxins or measurement of CO_2 production. In
the field investigation no attempt was made to use toxins.
Assuming that the changes in pH reflect CO_2 derived from
aerobic respiration, estimates of biological activity can be
made. The proportion of biological uptake was determined
from alkalinity and changes of pH in the experimental
chamber (Stumm and Morgan, 1970). The results of this
calculation are given in Table 1. Very small changes of pH
were recorded especially at low oxygen concentrations
resulting in high variations of calculated biological
uptake. The mean value of this uptake was estimated at 40%
of the total uptake which is in good agreement with the
values reported in the literature (Hargrave 1972a, Pamatmat
1971, Smith and Teal 1973).

Sediment Oxygen Demand - Laboratory Results

Time change of the oxygen concentration in a water column
overlaying sediment collected from the bottom of Hamilton
Harbour is shown in Figure 7. Sediment oxygen demand can
be calculated from the slope to this curve and a constant
which depends on the geometry of the measuring cell. From
the curve shown in Figure 7, it is apparent that the sediment
oxygen demand is decreasing as the oxygen concentration declines.
As mentioned in the experimental section, experiments at
every temperature level were repeated several times with
good reproducibility of the results. To calculate the
sediment oxygen demand from the curve shown in Figure 7 it is
advantageous to fit the experimental points by a mathematical
function and calculate the rate by differentiation. It has
been suggested (Edwards and Rolley, 1965) that for diffusion
accompanied by chemical reaction, the rate of the concentration
change depends on the oxygen concentration according to the
equation:

$$dc/dt = ac^b \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Here dc/dt is the rate (for example in mg/l/hr), c is oxygen concentration (mg/l) and a and b are constants. If this equation is valid than $\ln(dc/dt)$ should show straight line dependence on $\ln(c)$. Although there is considerable scatter, when the raw data are used to calculate dc/dt, this condition is met as shown in Figure 8. Above oxygen concentration of about 0.5 mg/l, the relationship between the sediment oxygen demand (or dc/dt) and oxygen concentration can be approximated by a straight line. The is in agreement with the field data results as shown in Figure 6.

Equation (1) can be solved to give dependence of oxygen concentration on time.

$$c = \left[a\,(1-b)\,t + q \right]^{\frac{1}{1-b}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Because at

time $t = 0$ concentration $c = c_o$ and therefore,
$q = c_o^{1-b}$, the equation can be rewritten

$$c = (a\,Bt + c_o^B)^{\frac{1}{B}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where:

$$B = 1-b$$

This is a two parameter non-linear equation between concentration and time. The coefficients a and B were calculated for every run by the Newton-Raphson method (Carnahan et al, 1969, pg. 322) with least square fit of increments in each step. The results of a typical fit are shown in Table 2. Several other types of equations, linear, quadratic, exponential etc. were tried for fitting of the oxygen concentration vs. time dependence. It was found that equation (3) fits the data best with a minimum of coefficients.

Results of all individual runs were fitted by equation (3)
and the final sediment oxygen demands for the individual
temperatures (averages of all runs) are shown in Figure 9.
Results at the three temperature levels were used to
interpolate and extrapolate to the 10°C to 25°C range
(Figure 10). This graph was also used to read data at
10° to 25°C range (Figure 10). This graph was also used to
read data at 10° and 20°C and to calculate Q_{10} (change of the
rate for 10°C change in temperature) given in Table 3. As
can be seen, Q_{10} varied from 1.64 to 1.99. Values close to
2 are considered to be normal for most of the biological and
chemical processes. The physical processes (diffusion, etc.)
do have smaller temperature gradients. For example, diffusion
in the 10 to 20°C range has Q_{10} approximately equal to 1.3
to 1.4

To see how much of the sediment oxygen uptake can be attributed
to the biological processes, runs with 4% (by weight) of
formalin in the water phase were carried out. The results
are shown in Figure 9. The decrease of the uptake rate is
significant. For 25°C average biological uptake was between
80 and 90% of the total (Table 4) with higher proportions
due to biological uptake at lower oxygen concentrations. The
ratio of biological to chemical uptakes is higher than that
determined from the field measurements. There may be several
reasons for it. In the laboratory experiments, the sediment
interface was not intact as the mud was actually mixed during
collection and its transfer into the measuring cell. There
is also a possibility that formalin in the solution is acting
as a retardant for the oxygen consuming chemical reactions.

Water Column Oxygen Demands

Water column oxygen demands were the most serious oxygen stresses
within the harbour. Resolution of these demands was difficult
because of the interactive nature of processes such as photo-
synthesis and photorespiration. Sources and demands were not
homogenous through the water column and rates varied during the
course of a 24 h period.

Although the vertical instability of the water column re-
sulted in changes of the mixing depth, photosynthesis was
considered to be confined to the euphotic zone. The euphotic
depth (Z_{eu}) was determined by measuring the vertical atten-
uation of green light ε_λ (490-570nm) using Talling's (1971)
relationship of

$$Z_{eu} = \frac{3.7}{\varepsilon_\lambda (490-570nm)} \qquad \dots \ (3)$$

Over the period of investigation the euphotic depth averaged
3.5 m.

Net photosynthesis measured as oxygen production ranged from
0.08 to 0.27 g O_2 m^{-3} h^{-1}. Respiration, measured as oxygen
consumption in dark bottles (for 3-4 hours), ranged from 0.033
to 0.25 g O_2 m^{-3} h^{-1}. These respiratory rates were generally
higher than the twenty-four hour in situ incubations which
ranged from 0.030 to 0.040 g O_2 $m^{-3}h^{-1}$. This might indicate
that photorespiration by both algae and bacteria can signifi-
cantly affect measurements of short time exposures. Samples
from the photic zone when placed in dark bottles continued
to respire at higher rates for short periods of time.

During the course of a 10 hour light day, net oxygen produc-
tion in the upper 3.5 m ranged from 0.62 to 1.62 g O_2 m^{-2}
d^{-1} from early June to late September. Photosynthesis
ameliorated 7 to 19% of the measured column oxygen demands,
although the material fixed by the phytoplankton eventually
created a potential oxygen demand when the cells became
moribund. Presently, algal and bacterial carbon are a minor
portion of the total organic carbon found in the harbour
waters, as particulate carbon was less than 2 mg l^{-1} and
total organic carbon was between 8 and 10 mg l^{-1}. Conse-
quently, the water column oxygen demand is not being limited
by the rates of carbon assimilation by the phytoplankton.

Biochemical oxygen demands (BOD_5) were high (particularly in
the hypolimnion) during the spring, and coincided with the
period when oxygen stocks of the harbour were being most

rapidly depleted (see Figure 6). Chemical oxygen demands (COD) were somewhat constant through the year and reflected the high oxidizable carbon content of the harbour water. Both the biochemical and chemical oxygen demand reflect the industrial and urban loadings to the harbour. Most of the water column demand was not from the oxidation of autochthonous carbon, but was resultant from point source discharges of organic material. Chemical oxygen demands were similar through the water column, but biochemical oxygen demands exhibited considerable variation with depth.

The results of water column oxygen demand measurements are shown in Figure 6 as crosses. The relation of water column oxygen demand and oxygen concentration can be correlated by a straight line significant at the 99% confidence level ($r = 0.758$). The dependence of the water column oxygen demand on oxygen concentration can be expressed as:

$$k_w = 0.24 + 0.07c \qquad (4)$$

where k_w is in g O_2 $m^{-3}d^{-1}$ and c is the oxygen concentration in mg l^{-1}.

The considerably lower correlation of water column demand probably reflects that much of the variability is related to other factors such as spatial distribution and nature of the bacterial communities.

Estimation of the Atmospheric Aeration

The method of difference was used to calculate the reaeration coefficient. The following oxygen demanding and consuming processes were considered:

Coefficient	Symbol	Unit
Water column oxygen demand	k_w	$g\ O_2 m^{-3} d^{-1}$
Sediment oxygen demand	k_s	$g\ O_2 m^{-2} d^{-1}$
Exchange through the Burlington Channel	k_e	$g\ O_2 d^{-1}$
Photosynthesis	k_p	$g\ O_2 m^{-2} d^{-1}$
Reaeration	k_a	$g\ O_2 m^{-2} d^{-1}$
Harbour volume	V	m^3
Harbour area	A	m^2
Time	t	d

Assuming that rainfall, contribution by tributaries and all other possible processes not listed above are not significantly contributing to the total oxygen balance, we can write for total change in oxygen stock (Δm) during some time period t_2 to t_1.

$$\Delta m = m_{t2} - m_{t1} = \int_{t_1}^{t_2} (k_e + Ak_p - Vk_w - Ak_s)dt + A \int_{t_1}^{t_2} k_a\ dt \quad ..(5)$$

Assuming that k_a is constant throughout this time period –

$$k_a(t_2 - t_1) = \frac{1}{A}(m_{t2} - m_{t1}) - \frac{1}{A} \int_{t_1}^{t_2} (k_e + Ak_p - Vk_w - Ak_s)dt \quad ....(6)$$

This equation can be used to calculate k_a for the time interval between the individual surveys assuming linear change of the oxygen concentration in between.

As an example, the calculation k_a for the period May 27 to June 18, 1976 when the stock and concentrations decreased nearly linearly (Figure 4) is presented:

Data:

Date 1976	Oxygen Stock 10^3 kg	Oxygen Concn. mgl^{-1}	Time d	Volume m^3	Area m^2
May 27	2874	10.3	0	2.80×10^8	2.15×10^7
Jun 18	677	2.4	23	2.83×10^8	2.17×10^7

We can write for the dependence of concentration on time.

$$c - 10.3 = \frac{2.4 - 10.3}{23 - 0}(t-0) \quad \dots\dots\dots\dots\dots (7)$$

$$c = 10.3 - 0.343t \dots\dots\dots\dots\dots\dots\dots (8)$$

The Individual Processes

a. Exchange through the ship channel:

Assuming that on an average 1% of the harbour volume is exchanged per day through the ship channel (MOE 1975) and that the lake water has oxygen concentration of 12 mg/l:

$$k_e = (V/100)(12-c) = V(0.017 + 0.00343t) \ gd^{-1} \dots\dots\dots (9)$$

b. Photosynthesis:

As mentioned above, net oxygen production in the upper 3.5 m of the water column ranged from 0.6 to 1.6, averaging 1.0 g $O_2 m^{-2} d^{-1}$.

$$k_p = 1.0 \ g \ m^{-2} d^{-1} \dots\dots\dots\dots\dots\dots\dots (10)$$

c. Water column oxygen demand:

Using equations (4) and (8)

$$k_w = 0.24 + 0.07c = 0.961 - 0.0240t \ g \ m^{-3} d^{-1} \dots\dots\dots (11)$$

d. Sediment oxygen demand:

From equations (2) and (8)

$$k_A = 0.72 + 0.26 \ c = 3.40 - 0.0892t \ g \ m^{-2} d^{-1} \dots\dots\dots (12)$$

For the given time interval, the average harbour volume $V=2.81 \times 10^8$ m^3 and average area $A=2.16 \times 10^7$m^2. Substituting equations (9) to (12) into (6) we can write for k_a:

$$k_a = \frac{-2197 \times 10^6}{2.16 \times 10^7 \times 23} - \frac{1}{2.16 \times 10^7 \times 23} \int_0^{23} \left| 2.81 \times 10^8 (0.017 + 0.00343t) + 2.16 \times 10^7 \times 1.0 \right.$$

$$\left. -2.81 \times 10^8 (0.961 - 0.0240t) - 2.16 \times 10^7 (3.40 - 0.0892) \right| dt$$

$$k_a = 5.1 \text{ g } O_2 \text{ m}^{-2}\text{d}^{-1}.$$

This is the average value of the atmospheric reaeration for the period between May 27 and June 18, 1976. Similar calculations were carried out for the other time periods and the averages are given in Table 5.

OXYGEN BUDGET

To see the relative importance of the individual processes, the harbour oxygen budget was estimated for three different periods of 1976. Spring (April 23 to June 19), when fast decrease of oxygen stock took place (Figure 4), summer (June 19 to September 3), with nearly steady conditions, and fall (September 4 to October 27), when the oxygen stock slowly decreased, were the major identified periods in this study. The main oxygen sources and sinks in the harbour are quantified in Table 6. The positive numbers indicate oxygen input or release from stock, the negative numbers oxygen consumption or return to stock. The water column of the harbour was divided into the epilimnion, (surface to 3 m depth) the metalimnion (3 to 7 m) and hypolimnion (7 m to bottom). The relatively thick metalimnion layer reflects the thermal instability of the harbour and internal waves.

The seasonal variability of the rates of oxygen inputs and losses is evident in Table 6. Lake-harbour exchange was most important during the summer, with the major influence being observed in the hypolimnion. It is likely that irregularities in the oxygen profiles (Figure 3) were wedges of cold lake water which eventually mixed with the anoxic hypolimnetic waters. These periodic inoculations of lake water were most beneficial during the summer as the dissolved oxygen concentrations of the replaced harbour water were low. This resulted in a net gain of oxygen stock, with oxygen being supplied to the more seriously depleted sections of the harbour.

Mean values of oxygen demands and sources are presented in Table 5. Although there is a definite seasonal trend in the relative importance of the different processes which interplay to determine oxygen concentrations and distributions, atmospheric reaeration dominated as an oxygen source, and water column demands were the critical oxygen sinks. With regard to the artificial mixing project, any stimulation of atmospheric reaeration and vertical exchange would be initially offset partially by increased oxygen demand in the water column and at the sediment water interface. This creates a lag effect before mixing increases the dissolved oxygen concentrations of the harbour.

Relation Between Sources and Sinks of Oxygen in Hamilton Harbour

Of the oxygen sources to the harbour waters, atmospheric aeration was found to be the most important process. Its contribution was estimated from the total oxygen balance, and 68 to 84 percent of the oxygen stock was related to atmospheric-water gas exchange. This process is aided by the natural instability of the water column which causes undersaturation in the epilimnion, thereby increasing diffusion of oxygen into the water mass. Artificial mixing noted in Figure 4 probably resulted partially from the mixing process stimulating reaeration.

Exchange of water through the ship canal, estimated to be 1% of the harbour volume per day, can contribute 6 to 19% of the incoming oxygen (Table 6). This process can operate during periods of stability, instability or homogenous mixing, and is an important source of oxygen to the hypolimnion during the summer when lenses of lake water with high oxygen content are found in the deeper waters. During periods of homogenous mixing harbour water is well aerated, and the exchange is a less significant source of oxygenated water.

Photosynthetic oxygen production was limited by the high vertical attenuation of solar energy and accounted for 9 to 13 percent of the total oxygen input. Attenuation coefficient ranged from 0.7-1.8 ln units m^{-1}, and combined with erratic changed in mixing depth photosynthetic productivity was reduced below the level expected from the eutrophic nature of the harbour waters. As illustrated in Figure 2 supersaturation from photosynthetic activity was not evident, nor were typical photosynthetic oxygen profiles. Although the actual rates of vertical transfer are not known, they definitely exceed the photosynthetic rates of net oxygen production as even the epilimnion is undersaturated for most of the summer (Figure 5).

Remaining sources of oxygen contribute less than 1% of the oxygen supplied to the harbour. Advective throughput from tributaries is only about 0.2% of the harbour volume per day and the oxygen concentrations of the incoming water were not much different from the epilimnetic oxygen levels. Contributions from rainfall or runoff were negligible.

Conclusions

The main processes involved in oxygen consumption in Hamilton
Harbour are water column and sediment oxygen demand. Both
of these processes were studied experimentally in the field
and it was found that both were oxygen concentration depen-
dent. This explained much of the seasonal variation of the
uptake rates. The relative importance of different oxygen
supply processes varied during the year, but atmospheric
reaeration remained the main source of oxygen at all times.
A considerable amount of oxygen entered the harbour through
the ship canal connecting the harbour with Lake Ontario.
This exchange and photosynthysis were relatively more
important during the summer months. In general, most of
the oxygen was used in the water column. An oxygen budget
indicated that surface reaeration and vertical transfer must
be enhanced to prevent the late spring oxygen depletion of
the harbour waters.

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Table 1

Sediment Oxygen Demand-in situ study. May 10 and May 14 measurements
at Station 252 (8m depth), all others at Station 270 (13.5m depth).

Date 1976	Mean Oxygen Concentration mg l^{-1}	Mean Temperature $^{\circ}C$	Sediment Oxygen Demand gO_2 $m^{-2}d^{-1}$	Estimated Biological Oxygen Demand % of Total Demand
May 10	9.7	10.8	3.41	33
May 14	9.4	11.9	2.82	26
June 9	7.2	15.3	2.64	16
June 25	0.19	14.0	0.59	93
July 7	3.5	16.0	1.45	35
July 15	3.6	14.8	1.71	58
August 19	0.80	15.1	1.11	30
October 5	4.8	14.7	2.08	48
October 7-8[a]	0.8	14.2	0.72	-
October 13-15[b]	3.0	13.3	1.77	26

[a] 26 h run

[b] 44 h run

TABLE 2

A TYPICAL FIT OF CONCENTRATION WITH TIME FOR
THE LABORATORY RUN

(9) HAM. HARB. MUD IN LAB., FEB. 17-18/77, 20 DEG. C

CALCULATED COEFFICIENTS OF EQUATION:
LN C = 1/B*LN (A*B*T+C0**B)

A = -0.21540   B = 0.72120   C0 = 6.66000

FOR THIS EQUATION DC/DT = A*C**(1-B)
WHERE (1-B) = 0.27880

TIME	DISS. O2 MG/L EXPTL	CALC	DIFF	DC/DT	SOD(G/M2/D)
0.0	6.66	6.66	-0.00	-0.366	-2.420
1.00	6.27	6.30	0.03	-0.359	-2.380
2.00	5.89	5.94	0.05	-0.353	-2.339
3.00	5.60	5.59	-0.01	-0.348	-2.306
4.00	5.21	5.24	0.03	-0.341	-2.260
5.00	4.85	4.91	0.06	-0.335	-2.215
6.00	4.56	4.57	0.01	-0.329	-2.178
7.00	4.24	4.25	0.01	-0.322	-2.134
8.00	3.95	3.93	-0.02	-0.316	-2.092
9.00	3.67	3.62	-0.05	-0.310	-2.050
10.00	3.36	3.31	-0.05	-0.302	-2.000
11.00	3.07	3.01	-0.06	-0.295	-1.950
12.00	2.79	2.72	-0.07	-0.287	-1.899
13.00	2.49	2.44	-0.05	-0.278	-1.840
14.00	2.20	2.17	-0.03	-0.268	-1.777
15.00	1.91	1.91	-0.00	-0.258	-1.709
16.00	1.68	1.66	-0.02	-0.249	-1.649
17.00	1.41	1.41	0.00	-0.237	-1.570
18.00	1.19	1.18	-0.01	-0.226	-1.497
19.00	0.92	0.96	0.04	-0.211	-1.394
20.00	0.75	0.76	0.01	-0.199	-1.317
21.00	0.56	0.56	0.00	-0.183	-1.214
22.00	0.38	0.39	0.01	-0.165	-1.089
23.00	0.24	0.23	-0.01	-0.145	-0.958

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TABLE 3

SEDIMENT OXYGEN DEMAND AND Q10 VALUES. LABORATORY RUNS

Dissolved Oxygen mg ℓ^{-1}	Sediment Oxygen Demand gm^{-2}d^{-1}		Q10
	10°C	20°C	
1	0.57	0.99	1.74
2	0.71	1.33	1.87
3	0.81	1.56	1.93
4	0.89	1.70	1.91
5	0.97	1.85	1.91
6	1.04	1.97	1.89
7	1.08	2.09	1.94
8	1.13	2.21	1.96
9	1.18	2.31	1.96
10	1.23	2.41	1.96

TABLE 4

BIOLOGICAL AND CHEMICAL SEDIMENT OXYGEN DEMAND, LABORATORY RUNS.

| Temperature | Dissolved Oxygen | Sediment Oxygen Demand | |
°C	mg ℓ^{-1}	Biological %	Chemical %
11.0	0.5	99.8	0.2
11.0	1.0	99.3	0.7
11.0	2.0	96.3	3.7
11.0	3.0	90.3	9.7
25.0	0.5	89.1	10.9
25.0	1.0	87.3	12.7
25.0	2.0	85.7	14.3
25.0	3.0	84.6	15.4
25.0	4.0	83.7	16.3
25.0	5.0	83.0	17.0
25.0	6.0	82.4	17.6
25.0	7.0	81.9	18.1
25.0	8.0	81.4	18.6
25.0	9.0	81.0	19.0
25.0	10.0	80.6	19.4

Table 5

AVERAGE VALUES OF THE OXYGEN CONSUMING AND PRODUCING PROCESSES

Process		Unit	Spring Apr.23-June 18	Summer June 19-Sept.3	Fall Sept.4-Oct.27
Water Column	epilimnion	$gO_2m^{-3}d^{-1}$	0.94	0.72	0.82
Demand	hypolimnion		0.75	0.32	0.59
Water Column Demand*		$gO_2m^{-2}d^{-1}$	10.6	6.4	9.0
Sediment Oxygen Demand		$gO_2m^{-2}d^{-1}$	2.5	1.0	1.9
Atmospheric Reaeration		$gO_2m^{-2}d^{-1}$	9.0	5.1	9.9
Lake-Harbour Exchange*		$gO_2m^{-2}d^{-1}$	0.7	1.4	1.0
Photosynthesis (mean value)		$gO_2m^{-2}d^{-1}$	1.0	1.0	1.0

*Per unit surface area of the harbour.

TABLE 6

OXYGEN BUDGET OF HAMILTON HARBOUR, VALUES IN % OF INPUT

			Spring April 23-June 18	Summer June 19-Sept.3	Fall Sept.4-Oct.27
I N P U T S	Atmospheric Reaeration		+84	+68	+83
	Lake-Harbour Exchange		+ 6	+19	+ 8
	Photosynthesis		+10	+13	+ 9
L O S S E S	Epilimnion (0 to 3m)	Water Column Demand	-28	-30	-23
		Stock Change	+ 4	- 1	-0.5
	Metalimnion (3 to 7m)	Water Column Demand	-27	-27	-22
		Stock Change	+ 5	- 2	- 6
	Hypolimnion (7m to bottom)	Water Column Demand	-45	-26	-32
		Stock Change	+14	- 1	-0.5
	Total Water Column	Water Column Demand	-100	-83	-77
		Stock Change	+23	- 4	- 7
	Sediment Oxygen Demand		-23	-13	-16
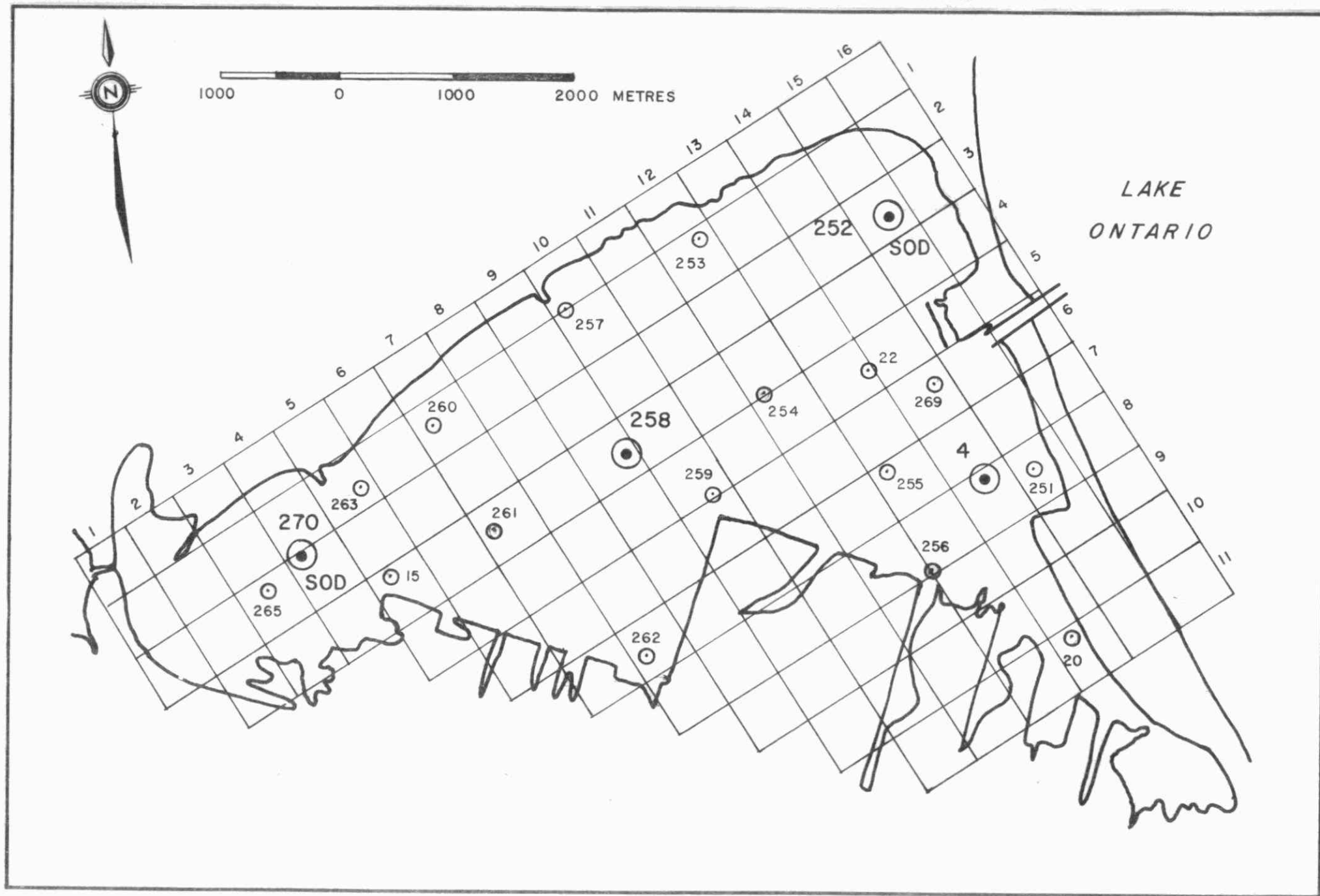
FIGURE I HAMILTON HARBOUR SAMPLING STATIONS AND GRID FOR OXYGEN STOCK CALCULATION.
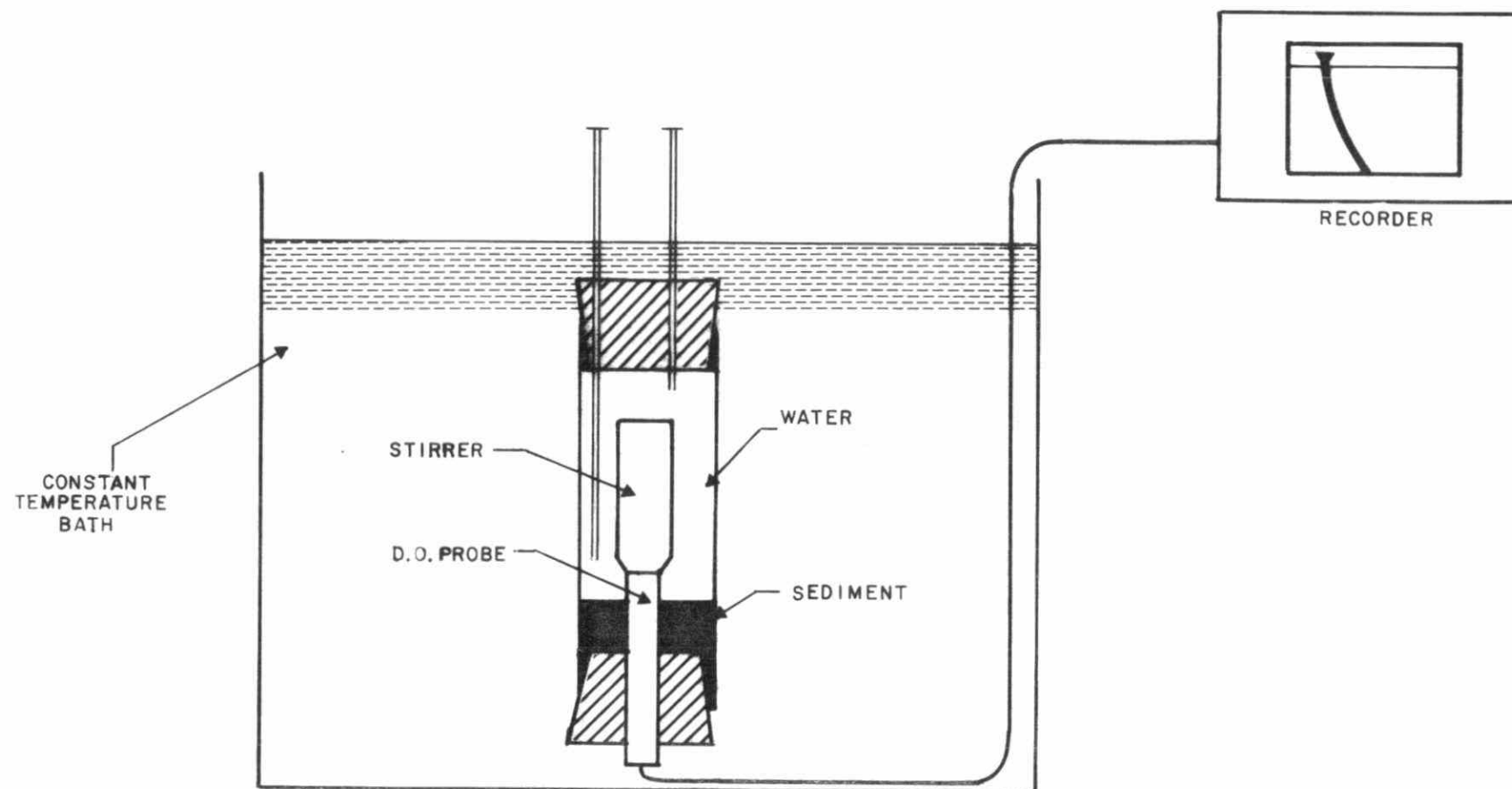
FIGURE 2 EXPERIMENTAL APPARATUS FOR MEASURING OF THE SEDIMENT OXYGEN DEMAND.
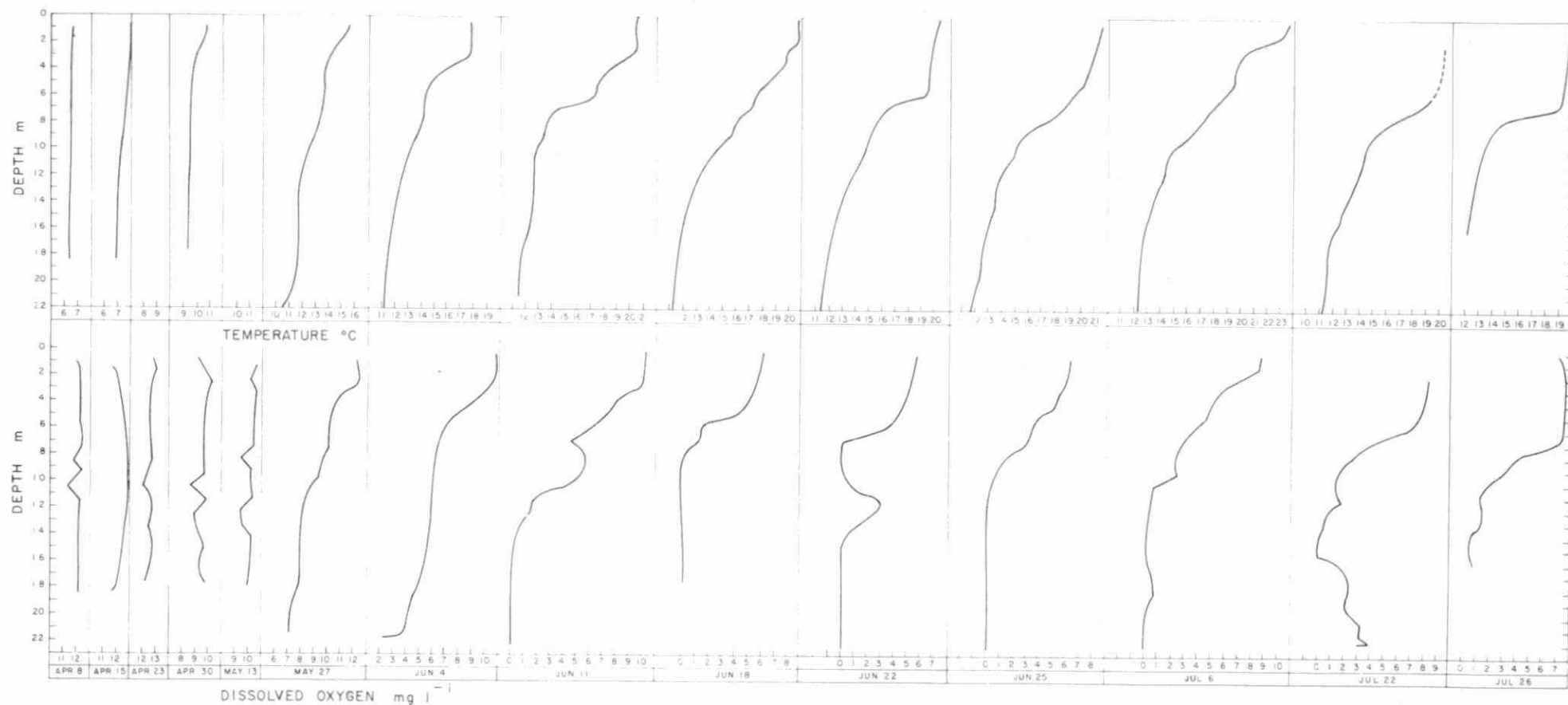
STATION 258

FIGURE 3a HAMILTON HARBOUR 1976. DISSOLVED OXYGEN DEPTH AND TEMPERATURE-DEPTH
PROFILES.

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STATION 258
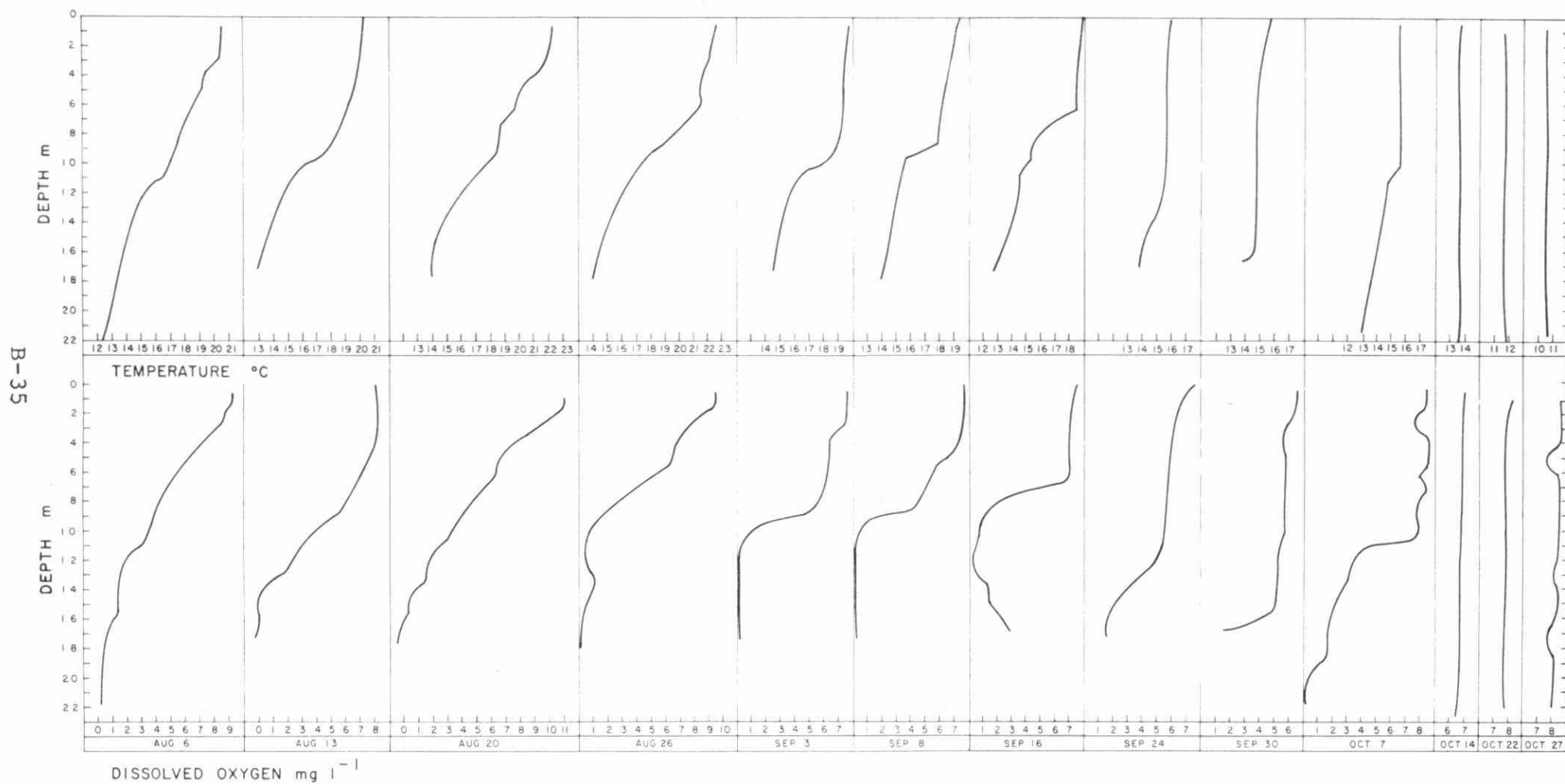
FIGURE 3b   HAMILTON HARBOUR 1976. DISSOLVED OXYGEN DEPTH AND TEMPERATURE- DEPTH
PROFILES.

B-35
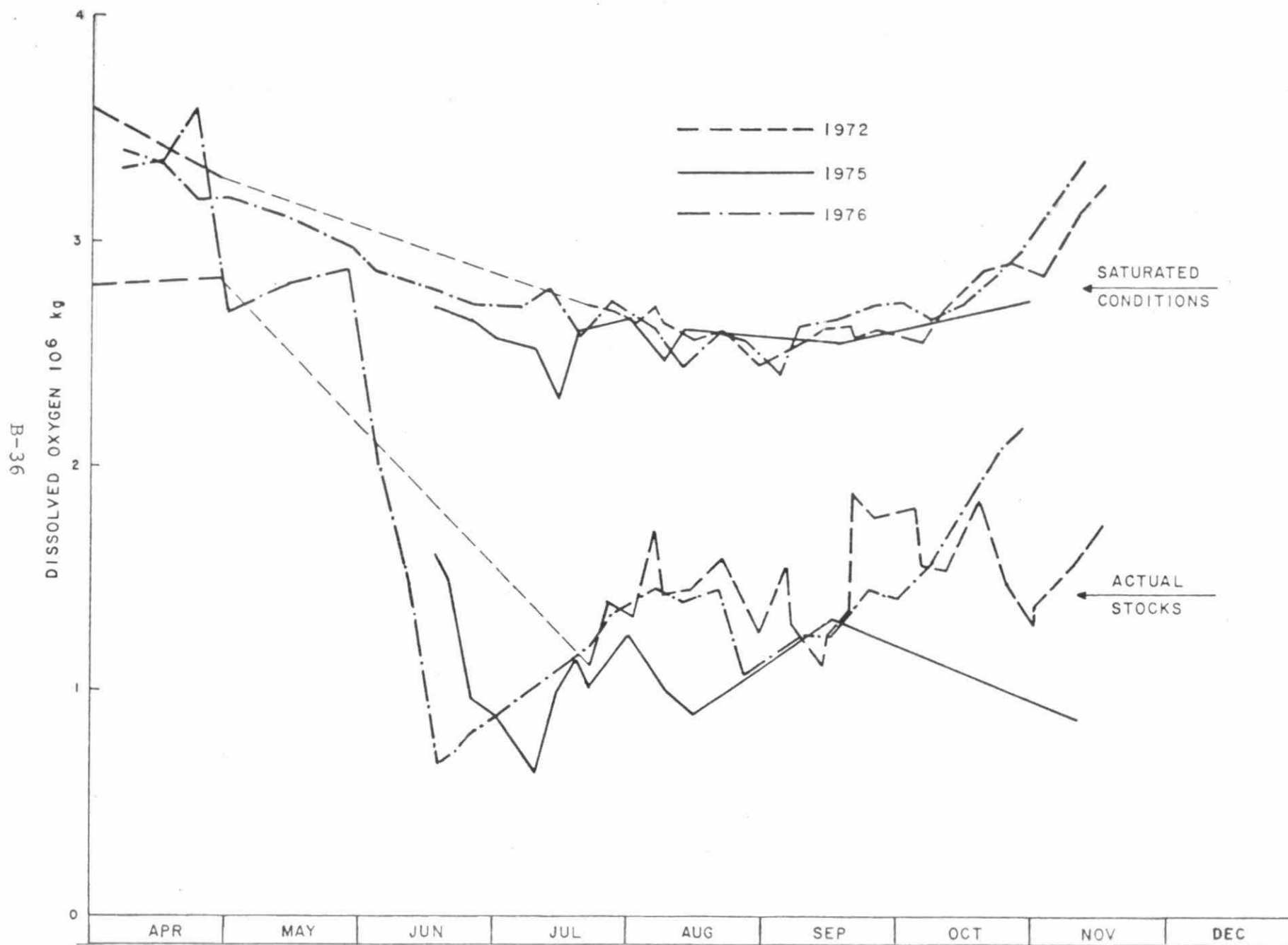
FIGURE 4 HAMILTON HARBOUR DISSOLVED OXYGEN STOCK.

B-36
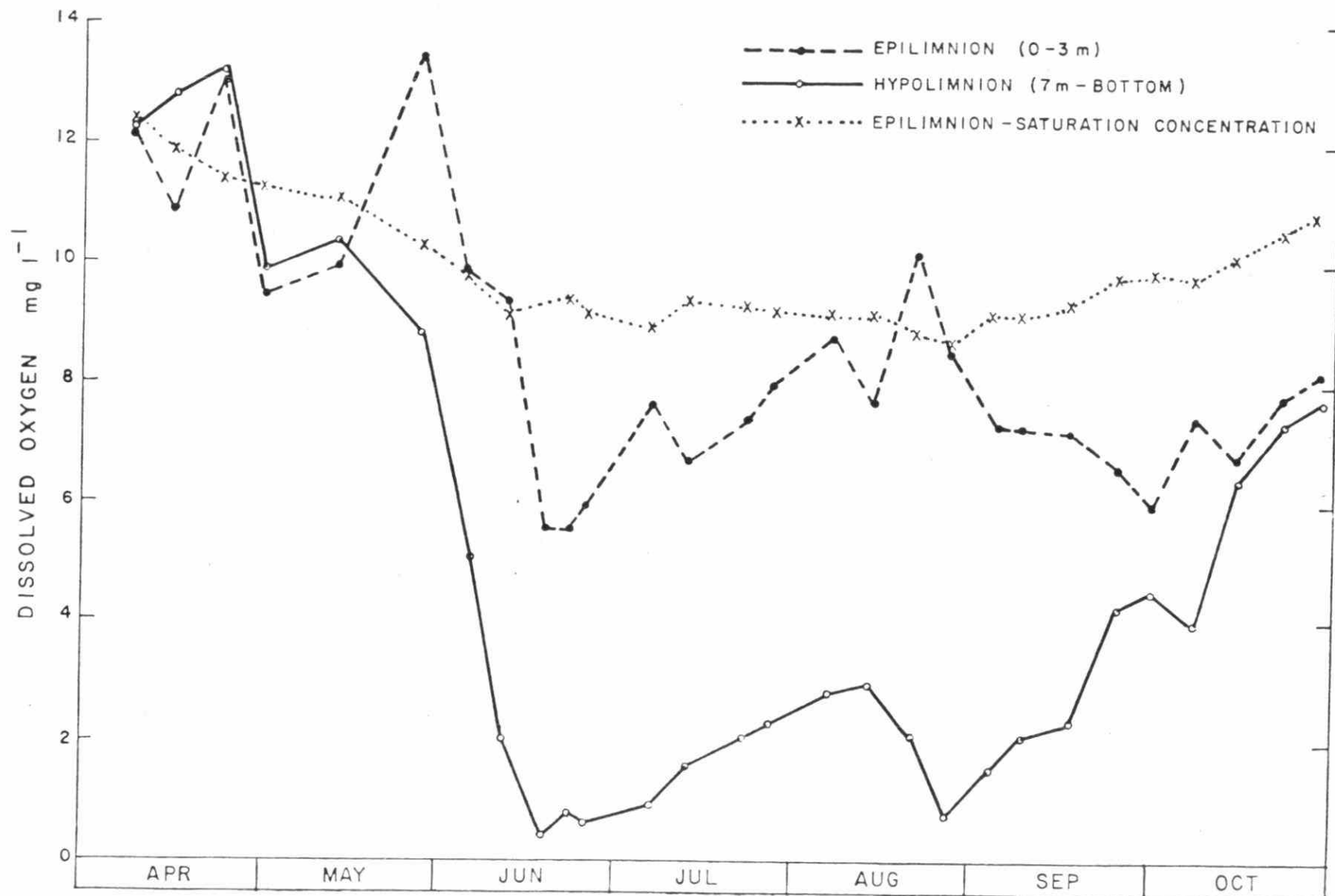
FIGURE 5   HAMILTON HARBOUR 1976. AVERAGE DISSOLVED OXYGEN CONCENTRATIONS.

B-37
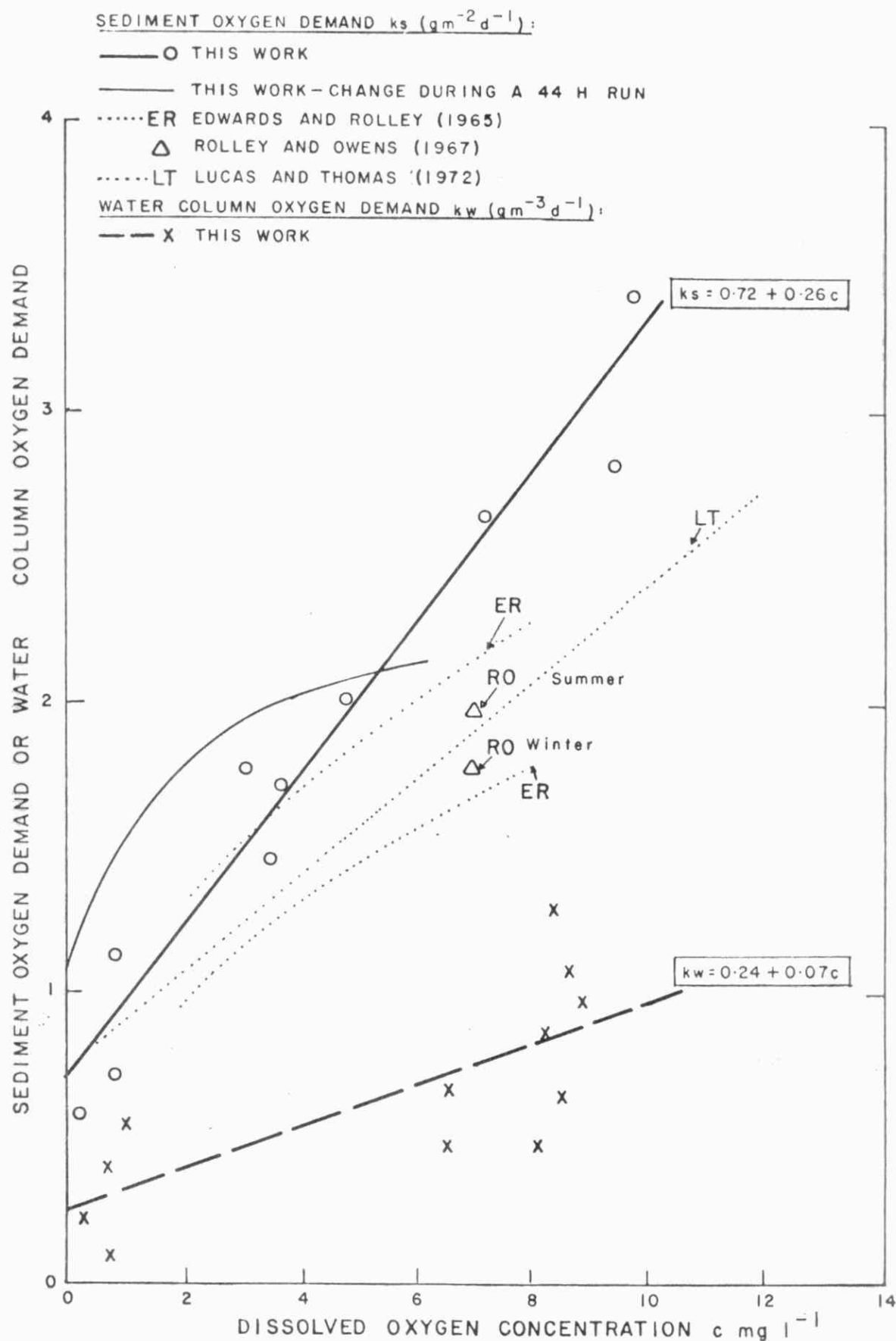
FIGURE 6 HAMILTON HARBOUR 1976. SEDIMENT OXYGEN DEMAND DETER
-MINED BY THE FIELD STUDY.

B-38
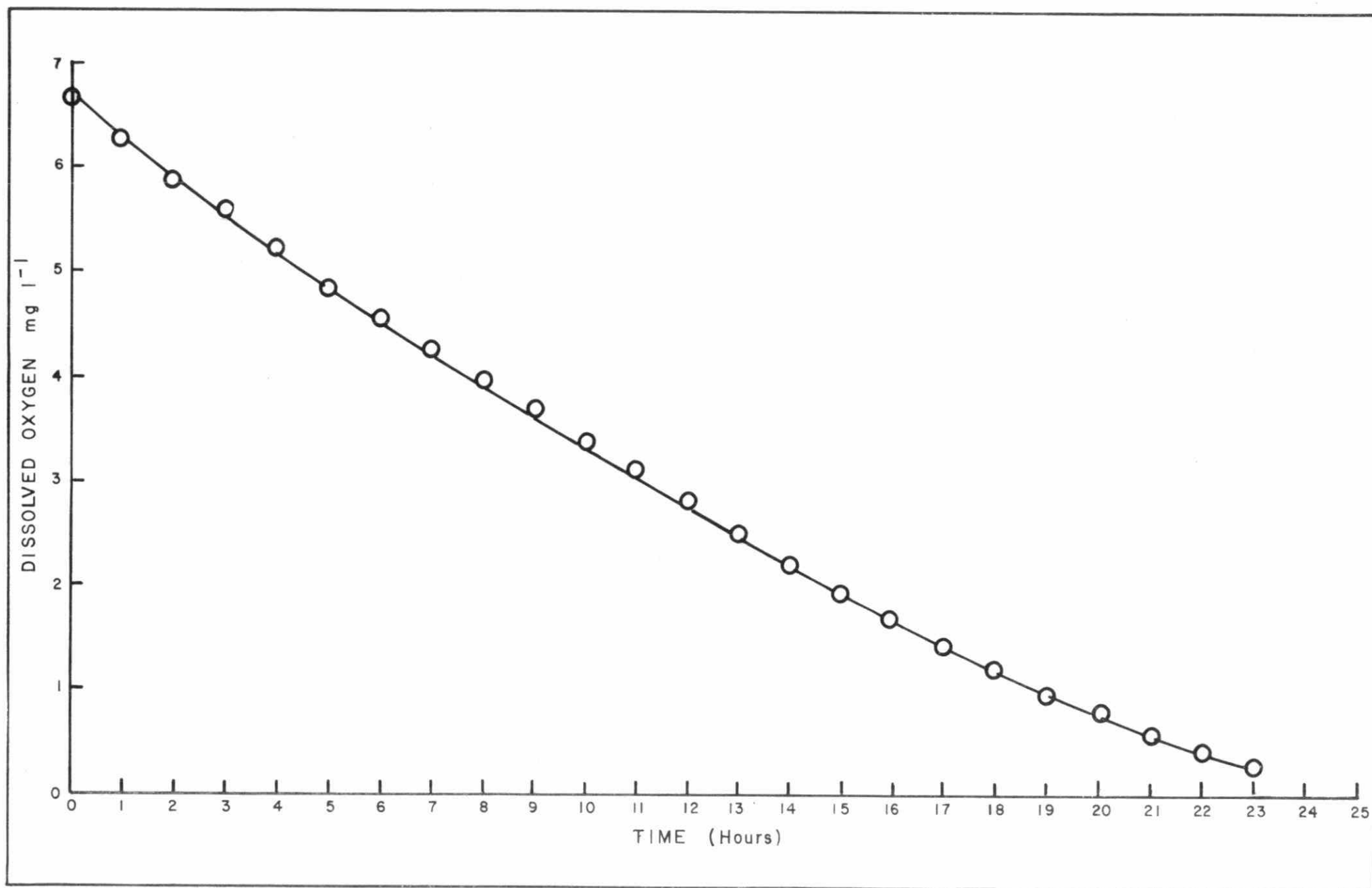
FIGURE 7 TYPICAL OXYGEN CONCENTRATION-TIME CURVE FOR LABORATORY RUN AT 25°C. SEDIMENT SEDIMENT FROM STATION 270, HAMILTON HARBOUR.

B-39
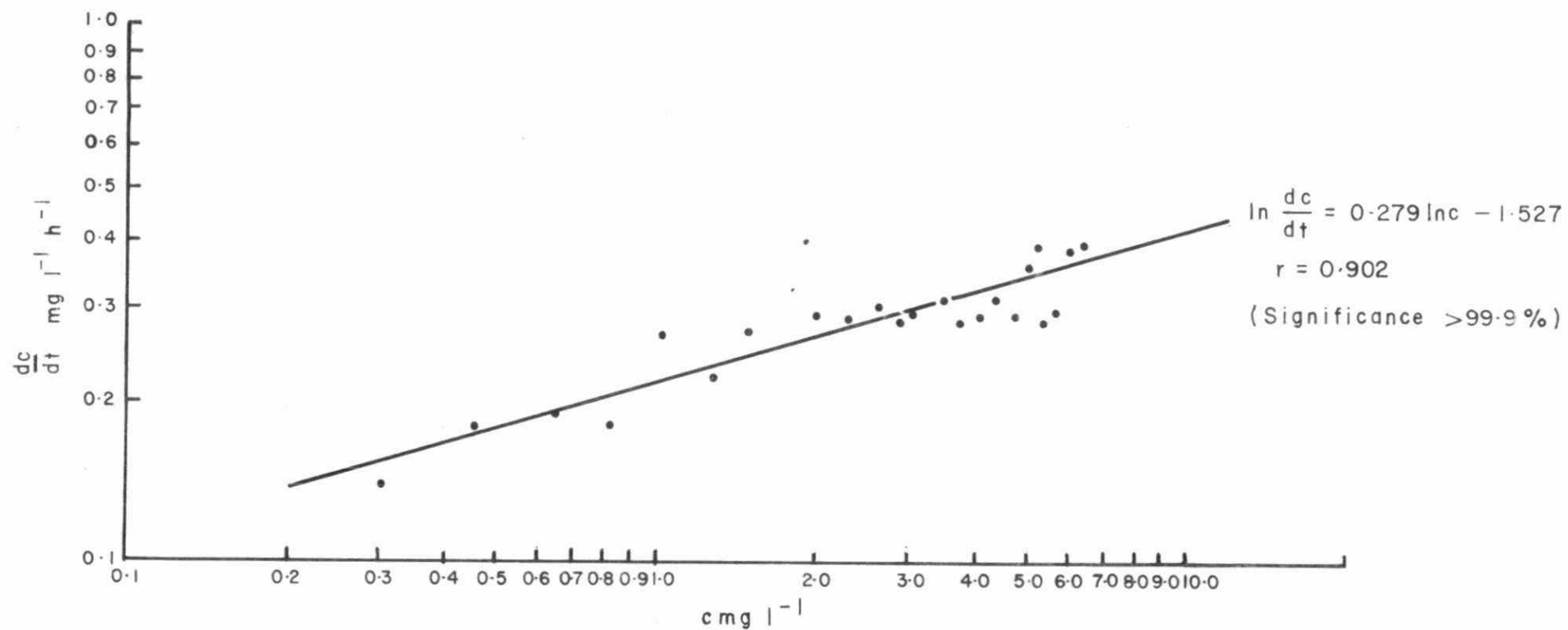
FIGURE 8 EXPERIMENTAL OXYGEN UPTAKE VERSUS CONCENTRATION.
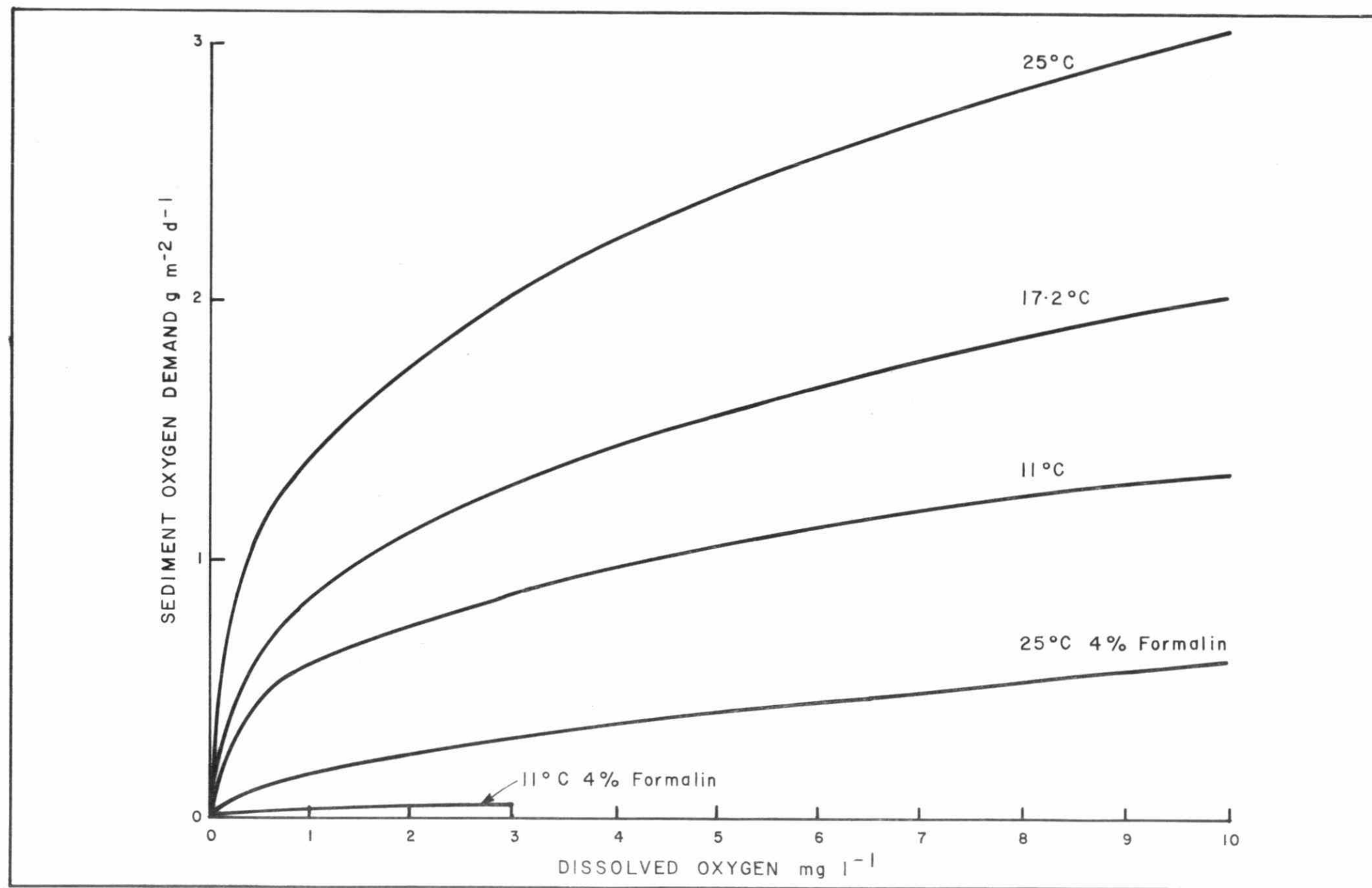
FIGURE 9 SMOOTHED EXPERIMENTAL DATA, SEDIMENT OXYGEN DEMAND, LABORATORY RUNS, SEDIMENT FROM STATION 270, HAMILTON HARBOUR.
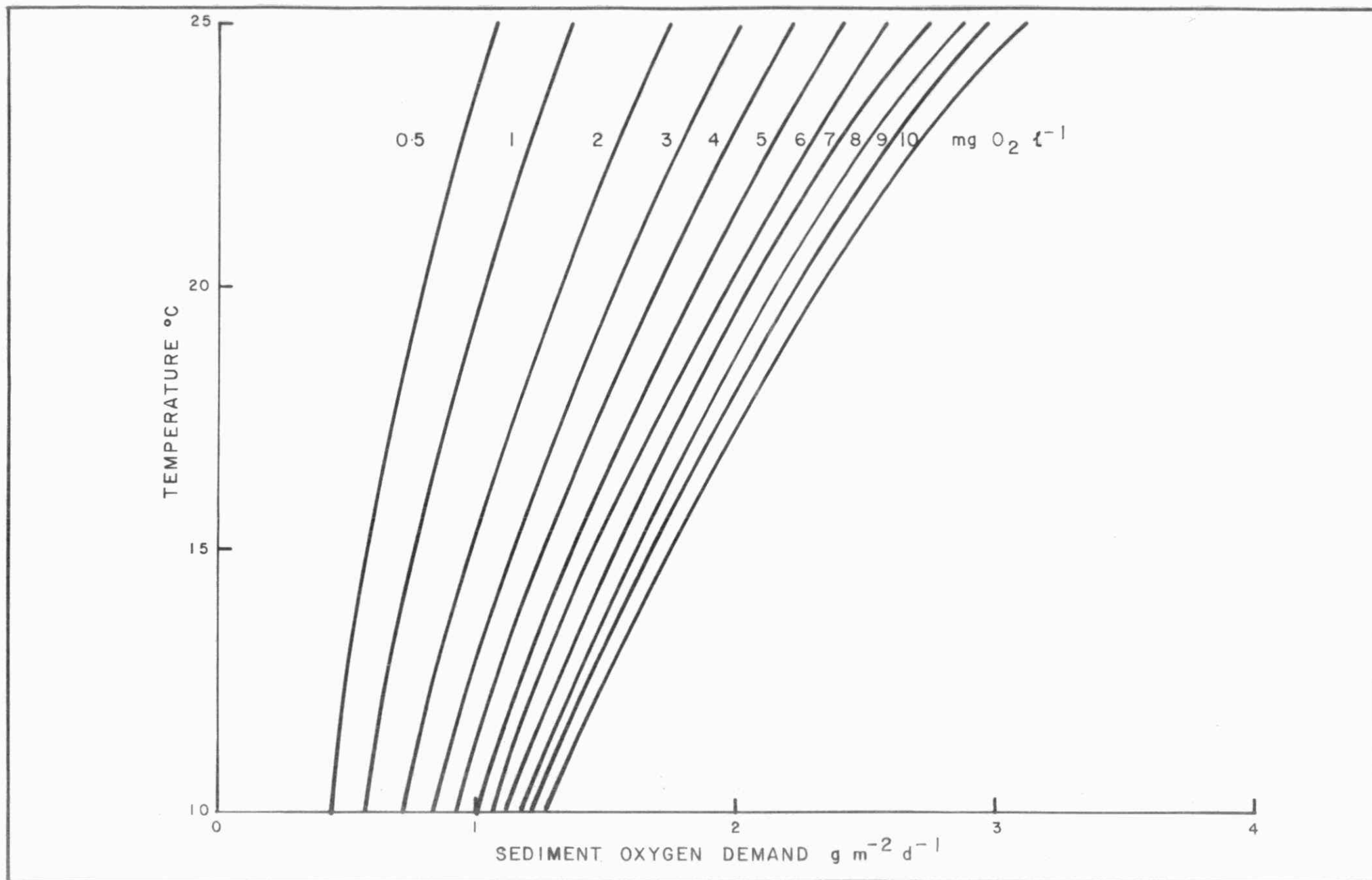
FIGURE 10 SEDIMENT OXYGEN DEMAND – TEMPERATURE – CONCENTRATION DEPENDENCE, LABORATORY RUNS, STATION 270, HAMILTON HARBOUR.
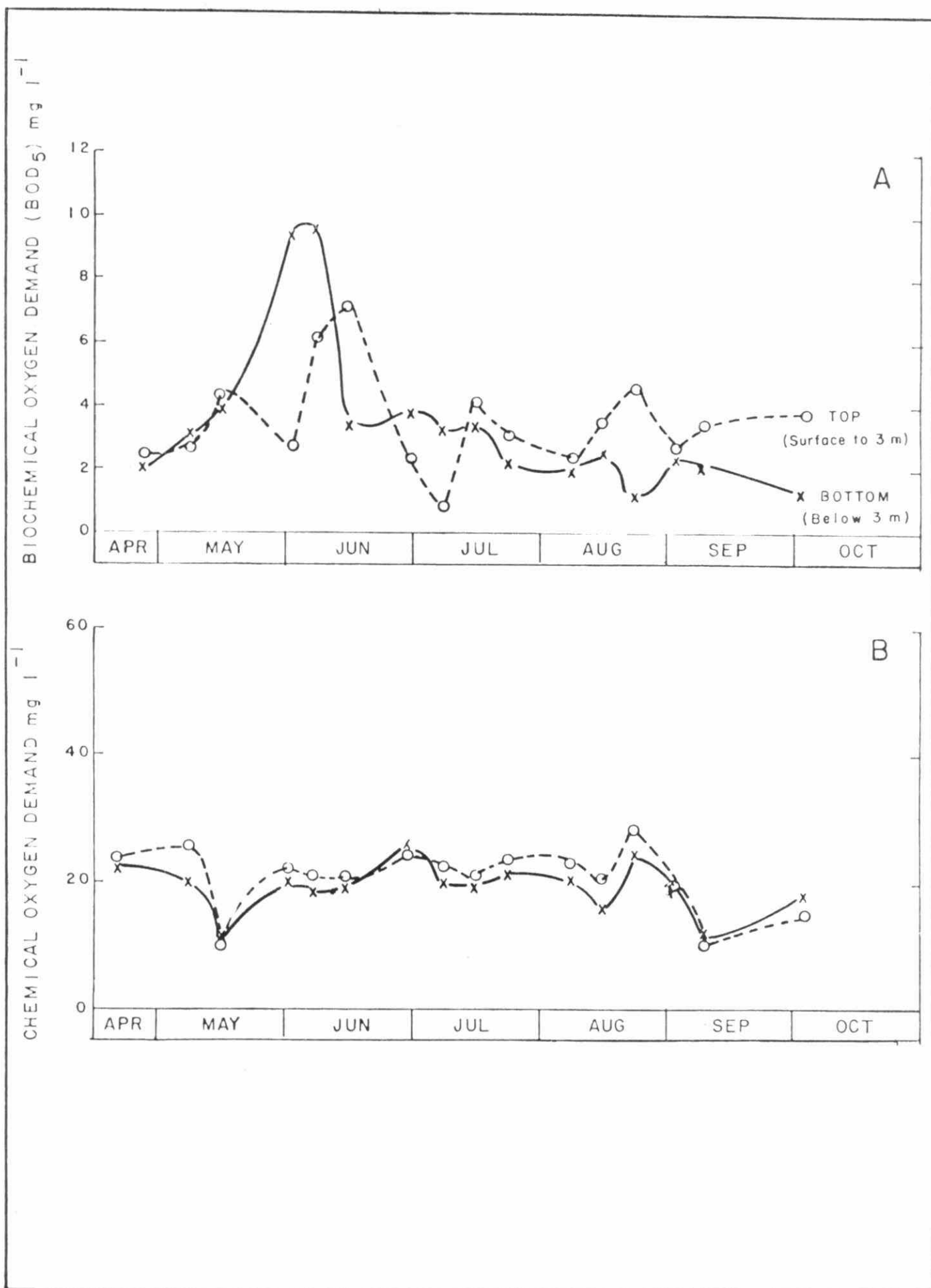
FIGURE II HAMILTON HARBOUR 1976. CHEMICAL AND BIOCHEMICAL OXYGEN
DEMANDS.

B-43

HAMILTON HARBOUR STUDY 1976

SECTION C

WATER QUALITY UPDATE

SUMMARY

The water quality survey program which was established in 1975, was
continued in 1976. It was found, that the seasonal and depth
variation of total Kjeldahl nitrogen (TKN), ammonia-N, nitrite-N and
nitrate-N were similar to those observed in 1975. The maximum mean
epilimnetic nitrite concentration was much lower than was observed
in 1975 and in general eplimnetic concentrations were below 0.2 mg/L.

The depth-time distributions of both TP and FRP again showed no
significant trends. The average values of 0.06 mg/L TP and 0.01
mg/L FRP are comparable to those concentrations observed in previous
years.

The average surface molar N/P ratio (TKN/TP) of Hamilton Harbour,
which was approximately 150, is a roughly three times that of Lake
Ontario and ten times that observed in algae. Therefore, the
harbour is greatly enriched with nitrogen compared to Lake Ontario
and algae.

The harbour-wide means of dissolved reactive silica (as Si) were far
lower in 1976 than were observed in 1975. The normal pattern of
lower epilimnetic concentrations, as compared with the hypolimnetic
concentrations, disappeared in mid-summer and silica became
vertically homogeneous presumably helped by artificial mixing.

The harbour-wide monthly means of zinc and iron showed no consistent
spatial and depth variations and only irregular seasonal
variations. Iron values, which were approximately 0.3 mg/L showed
irregular seasonal variations, but zinc values showed a seasonal
dependence with a summer maximum of 0.10 - 0.14 mg/L as compared
with concentrations of less than 0.10 mg/L at other times. Copper
values were found to be less than the detection limit of 0.01 mg/L
and manganese values were generally below 0.08 mg/L. The average
concentrations of iron and zinc were respectively at or in excess of
the IJC water quality objectives.

HAMILTON HARBOUR STUDY 1976
SECTION C
WATER QUALITY UPDATE

The intensive water quality survey program established in 1975 (MOE,
1977) was continued in 1976. Four stations representative of
various areas of the harbour (Figure 1) were surveyed once every two
weeks from late April to the commencement of artificial mixing in
June, and then approximately weekly until late August, and
irregularly thereafter. Weekly depth profiles of temperature,
dissolved oxygen (DO), redox potential, pH and conductivity were
also taken during the field season. The purposes of the chemical
survey were to extend the knowledge of water quality trends in
Hamilton Harbour, to assess the dissolved oxygen deficit and measure
the effects of abatement procedures in operation.

In this section, the observed harbour water quality in 1976 is
briefly summarized with reference to the control measures where
appropriate. It is planned to include a detailed discussion of the
1976 water quality including year-to-year trends in a combined
1976-77 water chemistry section in the forthcoming Hamilton Harbour
Study 1977 report.

Redox Potential and Dissolved Oxygen

In Figure 2, the depth-time distributions of redox potential are
plotted. The average observed value of about 200 mv is much lower
than expected for oxygenated surface waters (Hutchinson, 1957).
This may have been caused by exposure of the redox probe to
sulfide-containing sediments, thus producing a platinum sulfide film
which results in low, drifting potentials, or various iron redox
couples. Otherwise, it is difficult to explain the observed results.

The depth-time distributions for dissolved oxygen are plotted in
Figures 3a-3d. In these figures, anoxic or near-anoxic conditions
(1 mg/l DO) are shown as shaded zones. The effect of harbour
instability is observed as a series of oscillations in the depth of
constant DO values during the summer months.

Next to the sediment-water interface, lenses of water with increased
DO were observed during July. This bottom water oxygenation may
have been caused by both lake-harbour exchange and artifical
mixing. Cold lake water flowing in through the canal sinks to the
appropriate density level and mixes with harbour water. Artificial
mixing would possibly aid in the dispersion of the oxygenated lake
water due to the increased exchange with depth. However, the bottom
water oxygenation was most effective only in July. Both mechanisms
of DO enhancement should have been effective during August, but DO
levels remained below 1 mg/l throughout August at both stations 4
and 258.

A possible explanation for this phenomenon may be the reversed flow
scheme observed during automatic water chemistry monitoring in the
ship canal in August 1973 (MOE, 1974, Section A). During much of
this period, warm hypolimnetic harbour water flowed out through the
canal under cooler epilimnetic lake water. This was evidenced by
low DO and high conductivity values near the bottom of the canal.
If the thermal structure of the harbour and lake are such that this
occurs more frequently in August than in July, then the harbour DO
could be depleted rapidly in August because of sediment and water
column oxygen demand. Current meter operations associated with the
mass exchange program should have detected this phenomenon if it
existed; however, the current meters located nearest the canal
bottom have failed to produce any useful data.

Experimental studies of sediment oxygen demand and computation of
the harbour DO stock have been discussed elsewhere (Section B,
Oxygen Budget) and will not be repeated here.

Nutrients

Figures 4 to 7 show the depth-time distributions of ammonia-N, total
Kjeldahl nitrogen (TKN), nitrite-N and nitrate-N for 1976
respectively.

The seasonal and depth variations of these parameters were similar
to those observed in 1975 (MOE, 1977), with maximum NH_3 and TKN
concentrations occurring in May and maximum surface NO_3
concentrations occurring in July to early September. Epilimnetic
NH_3 values were again higher than hypolimnetic values, reflecting
the surface nature of the discharges. Surface organic N
$(TKN-NH_3)$-N values showed an irregular seasonal variation, with
maximum concentrations of around 1 mg/l being observed during most
(but not all) surveys during July and August. This tendency toward
higher summer organic-N values does not correlate with other
parameters such as NO_2-N, chlorophyll a, or total organic carbon.

The maximum 1976 epilimnetic mean NO_2-N concentration of 0.35 mg/l
(June 14) was much lower than the extreme value of 1.1 mg/l NO_2-N
observed during 1975. Except in late August and early September,
when concentrations of 0.25 to 0.3 mg/l were observed, epilimnetic
NO_2-N concentrations were generally below 0.2 mg/l. Epilimnetic
concentrations tended to be slightly higher than hypolimnetic
concentrations during most of the summer.

Although the seasonal pattern of nitrate concentrations in 1976 was
similar to that observed in 1975, the changes were less regular. In
early June, nitrification or N release at the sediment-water
interface allowed a build-up of NO_3-N in the hypolimnion of the
deep water stations. With the onset of anoxic conditions an
irregular decrease in hypolimnetic NO_3-N occurred, with a minimum
value being reached July 20. During early August a gradual increase
of bottom NO_3-N occurred, apparently connected with aerator
operations; however, epilimnetic nitrate concentrations remained
higher than hypolimnetic concentrations for most of the summer.

After late August, denitrification occurred at the sediment - water interface, under near - anoxic conditions. The trend of the NO_3-N concentrations in the deepest waters, however, seemed to parallel the existence of oxidized conditions at the sediment-water interface.

Depth-time distributions of total phosphorus and filtered reactive phosphorus (glass fibre filter) are given in Figures 8 and 9, respectively. As in previous years, no significant trends with regard to season or depth are evident. Average values of 0.06 mg/l (total P) and 0.01 mg/l (dissolved reactive P) are similar to values observed in recent years (MOE, 1977), considering the fact that standard deviations are in the range of 50 to 100% of the means (including sampling variations).

Little, if any evidence is available from our survey data for release of total or soluble phosphorus from the sediments. Piccinin (1977) found a very high (but unstated) level of soluble reactive phosphorus at station 4 near the end of August. Such a peak may easily have occurred between successive MOE sampling dates and have been missed; certainly there is no evidence here to confirm or deny this peak. Piccinin (1977) indicated the hypolimnion to be anoxic at the end of August; MOE data indicated about 3 mg/l DO at the bottom on August 23, but the DO monitor failed to function properly on August 30 or September 7; consequently, no proof of hypolimnetic anoxia at the end of August is available.

Ammonia concentrations in Hamilton Harbour are higher than the Ontario public surface water criterion value of 0.5 mg/l (MOE, 1973), except after about the end of August. All nitrate + nitrite values are well below the criterion of 10 mg/l. As the phosphorus criterion simply states "not encourage growth of algae or interfere with treatment process" (MOE, 1973), it is more interesting to compare P values or N/P ratios with other Great Lakes areas. The average surface molar N/P ratio in Hamilton Harbour is 150 ± 30. According to available data summarized by IJC (1969), the surface molar N/P ratio in Lake Ontario is about 44 during the summer,

assuming near zero nitrate -N concentrations as indicated in their Figure 2.3.17. According to Shiomi and Chawla (1970), summer NO_3-N is about 30 ug/l, but total P is 24 ug/l, rather than 15 ug/l as stated by IJC (1969). Combining these data with the IJC (1969) TKN figures gives a summer molar N/P ratio of 30.

These figures may be compared with the average N/P ratio in algae of 16. Thus the harbour is relatively enriched with nitrogen compared to Lake Ontario and average algae. This is perhaps due to control of P by Fe^{3+} in the harbour, although control of P concentration at the sediment - water interface appears to be more complex, as discussed elsewhere (Section D, Sediment Chemistry).

The seasonal dependence of surface and bottom harbour-wide means of dissolved reactive silica (as Si) is given in figure 10. The spring concentrations of 0.6 to 0.8 mg/l are far lower than those observed in 1975. With development of thermal stratification, both epilimnetic and hypolimnetic concentrations again decreased, with epilimnetic values being lower than hypolimnetic due to uptake by diatoms. In July, homogeneous concentrations were observed, presumably in response to artificial mixing, again as in 1975. However, the homogeneous concentrations were more closely related to the period of maximum hypolimnetic DO (mid-July), as opposed to the period of highest aerator flow, which extended to the end of August. In August, irregular changes in Si concentration occurred, including large variations across the harbour. These changes did not relate to any other parameter or to the artificial mixing program. After mid-August, hypolimnetic Si concentrations were again higher than epilimnetic; this condition persisted until overturn. The latter observation was similar to 1975, but overall concentrations were lower than those in 1975. It was suggested (Section A, Artificial Mixing) that the vertical instability of the harbour during the mixing period is responsible for a rapid flux in various diatom species, although a significant population remained throughout the season. It is possible that the irregular variations in silica content observed in August could be related to this rapidly changing biophysical environment.

Heavy Metals

In 1976, iron and zinc were determined from all sampling points at
every survey. The purpose of determining zinc was to assess the
extent of toxicity to the harbour algae. Piccinin (1977) determined
that zinc has a toxic effect on the alga Scenedesmus quadricanda at
concentrations above 0.01 mg/l, although she states that algae
cultured from Hamilton Harbour show an increased tolerance to zinc
toxicity and that response of various species to zinc concentrations
below 1 mg/l is inconsistent.

As the zinc and iron concentrations showed no consistent spatial and
depth variations and only irregular seasonal variations,
harbour-wide monthly means were calculated. These data are given in
table 1. Mean iron values are approximately 0.3 mg/l. The highest
individual Fe results occurred at station 4 on July 13 and September
8, when a concentration of 1.50 mg/l was observed. As this value
was observed in the epilimnion, it is related to the industrial
discharges and not to any sediment-water interaction.

The average Fe value of 0.3 mg/l is identical to the IJC (1977)
Great Lakes Water Quality Objective figure, thus indicating the
existence of a water quality problem. Zinc concentrations showed a
seasonal dependence with a summer maximum of 0.10-0.14 mg/l in June
to July. Concentrations were below 0.1 mg/l in the remainder of the
season. As the IJC Water Quality Objective is 0.03 mg/l Zn, a
definite water quality problem exists for this metal at all
seasons. The results of individual surveys during June and July,
however give a variation from below 0.05 mg/l on June 14 to above
0.4 mg/l at stations 252 and 258 on July 6 and 13. It is difficult
to relate these changes to the mixing program or to any biological
parameter.

Samples taken in the September - November period were also analyzed
for manganese and copper. In all cases, copper concentrations were
0.01 mg/l or less. Except for hypolimnetic samples in September, Mn

values were below 0.1 mg/l. At stations 4 and 258, the hypolimnetic
Mn values were 0.2 to 0.5 mg/l. This result is reasonable because
manganese is released under less severe reducing conditions than
iron. The redox potential to obtain 10^{-5}M (about 0.6 mg/l)
concentrations of Mn and Fe corresponds to a pE of about 8 for Mn
and 2 for Fe at a pH of near 7 (Stumm and Morgan, 1970, p.533). As
the Ontario public surface water supply criterion for Mn is 0.05
mg/l, these figures represent a water quality problem for this
metal. That water quality problems exist for Fe, Zn and Mn is not
surprising since the harbour sediments are known to be highly
polluted with respect to these metals (section D, Sediment
Chemistry; MOE, 1977, Section C).

Events occurring at the sediment-water interface play a strong role
in regulating aqueous heavy metal and nutrient concentrations
(Hutchinson, 1957; Stumm and Morgan, 1970). This topic has been
discussed more thoroughly (Section D, Sediment Chemistry), and
suggested future projects including partial extraction of sediments
and study of the chemistry of the water next to the interface are
proposed in that section.

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Stumm, W., and J.J. Morgan, 1970. Aquatic chemistry. John Wiley and Sons, New York, 583 p.

TABLE 1

Harbour-wide monthly means of iron and zinc concentrations,
Hamilton Harbour, 1976 (mg/l).

	Iron	Zinc
April	0.33	0.07
May	0.33	0.06
June	0.19	0.14
July	0.46	0.10
August	0.27	0.06
September	0.38	0.06
October	0.16	0.06
Period	0.30	0.09
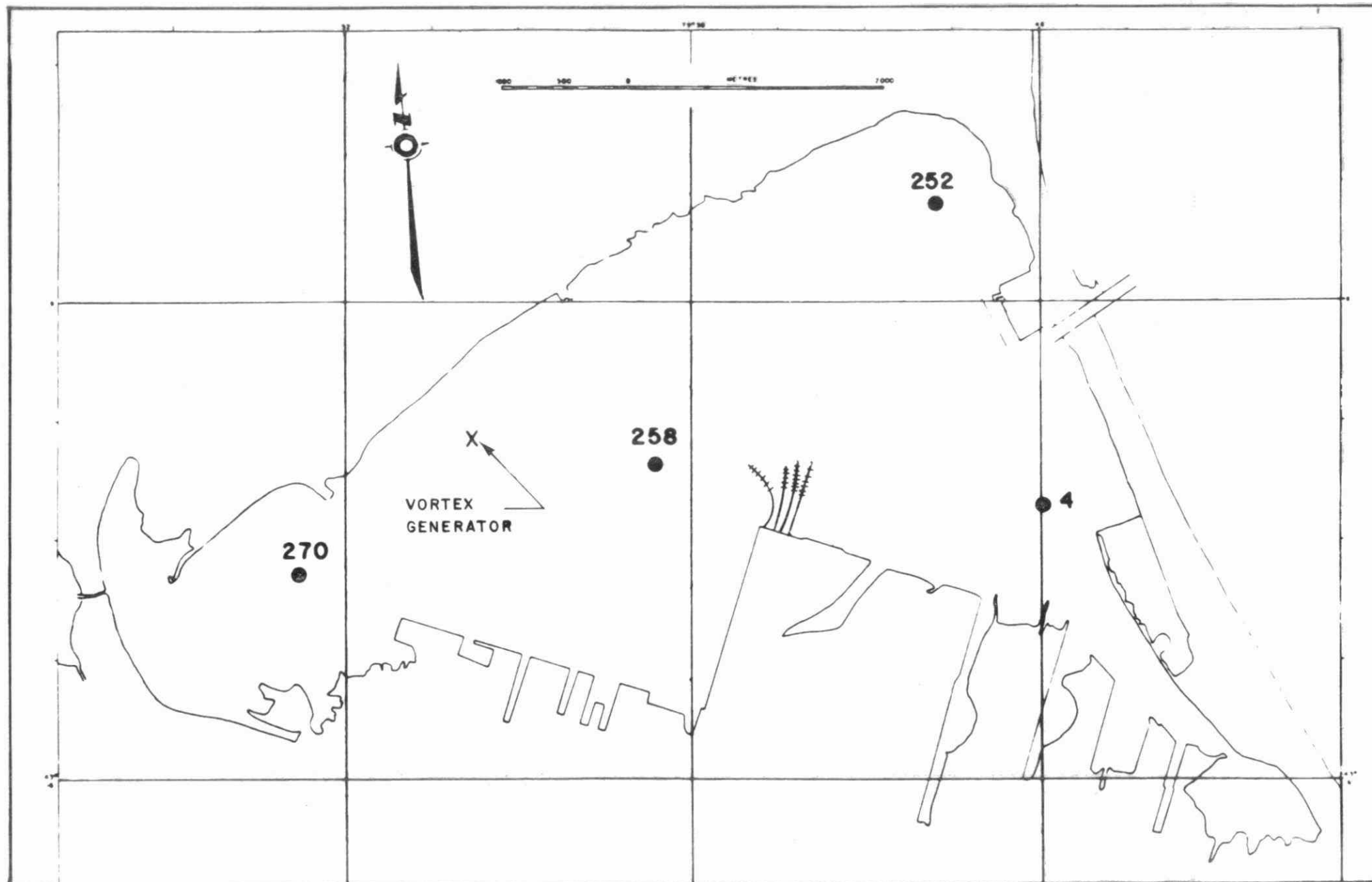
FIGURE 1: HAMILTON HARBOUR ILLUSTRATION DIFFUSER LINE, POSITION OF VORTEX GENERATOR AND MAJOR SAMPLING STATIONS
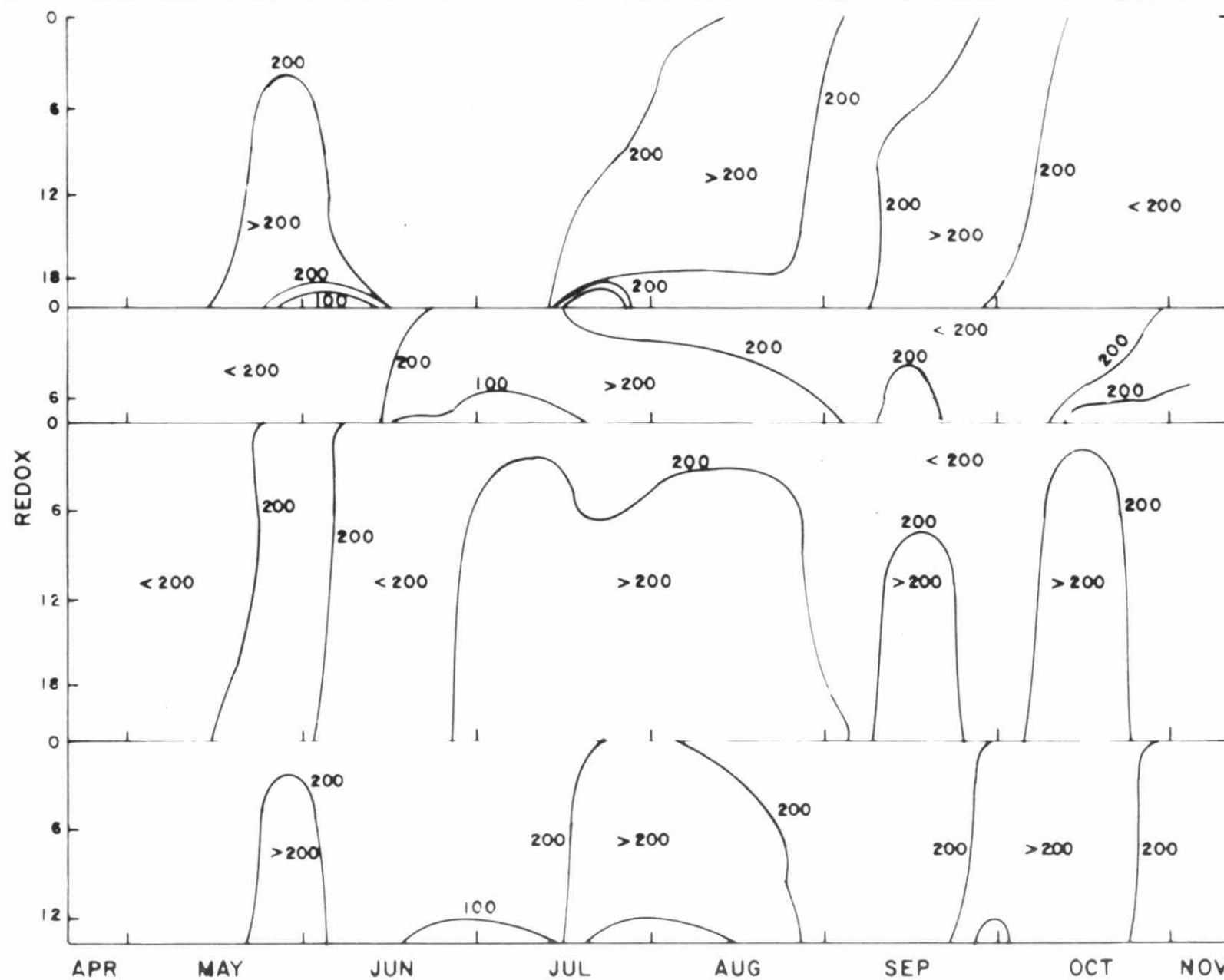
FIGURE 2 ISOPLETHS OF APPARENT REDOX POTENTIALS (mv) AT FOUR MAJOR SAMPLING STATIONS HAMILTON HARBOUR
1976
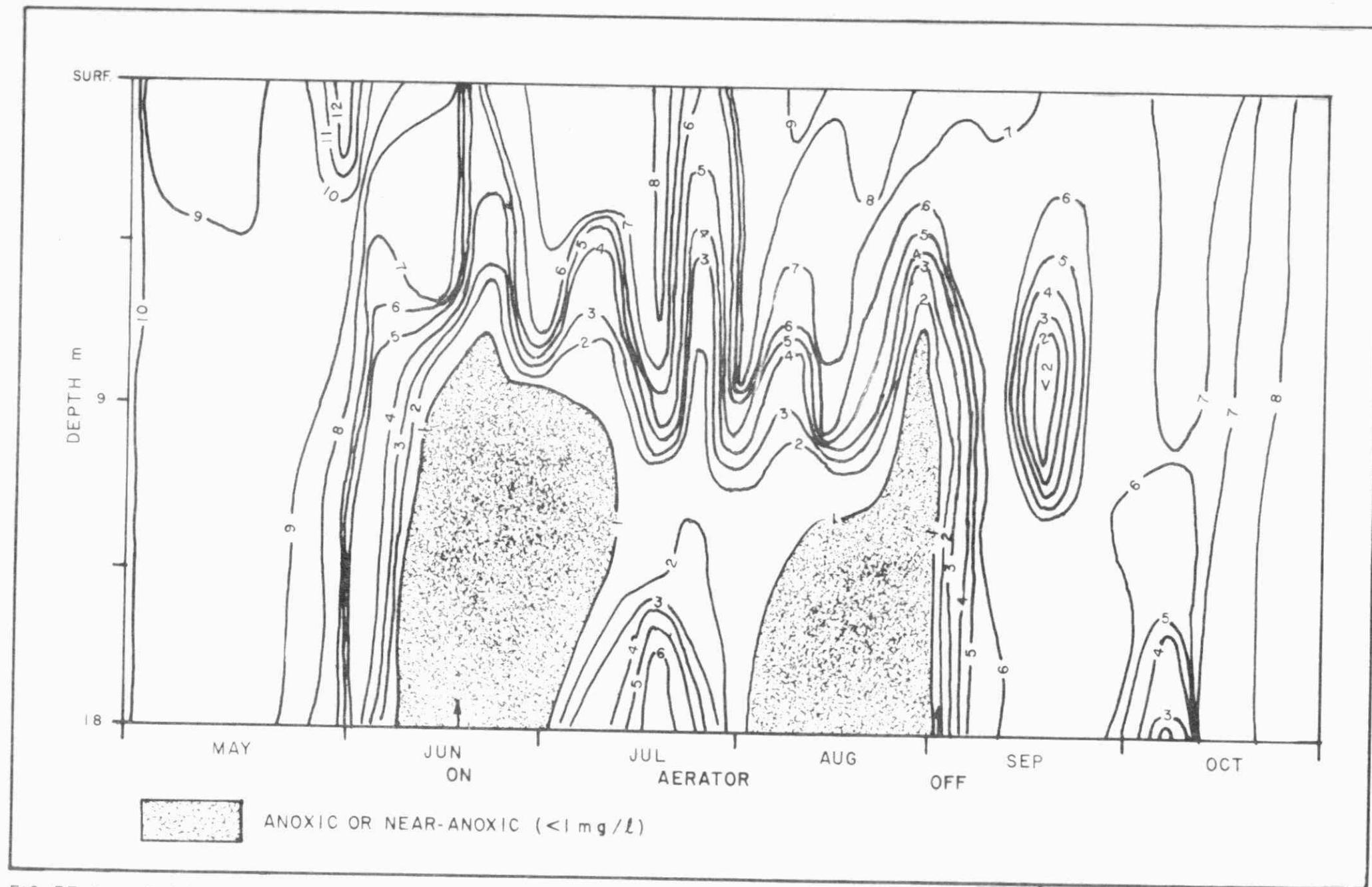
FIGURE 3a : DISSOLVED OXYGEN PROFILES (mg/ℓ) HAMILTON HARBOUR 1976, STATION 4

ANOXIC OR NEAR-ANOXIC (<1 mg/ℓ)
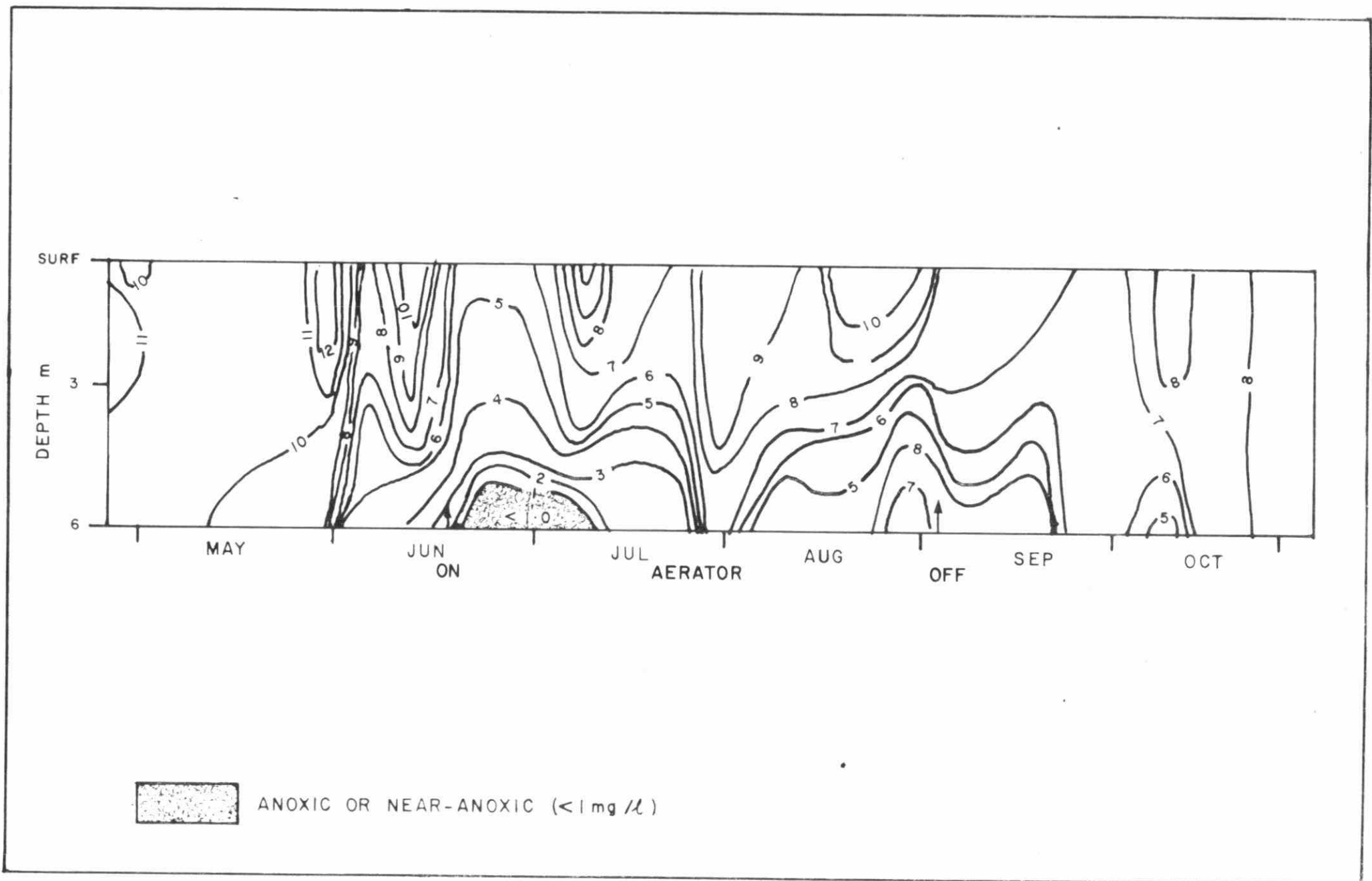
FIGURE 3b: DISSOLVED OXYGEN PROFILES (mg/ℓ) HAMILTON HARBOUR 1976 STATION 252
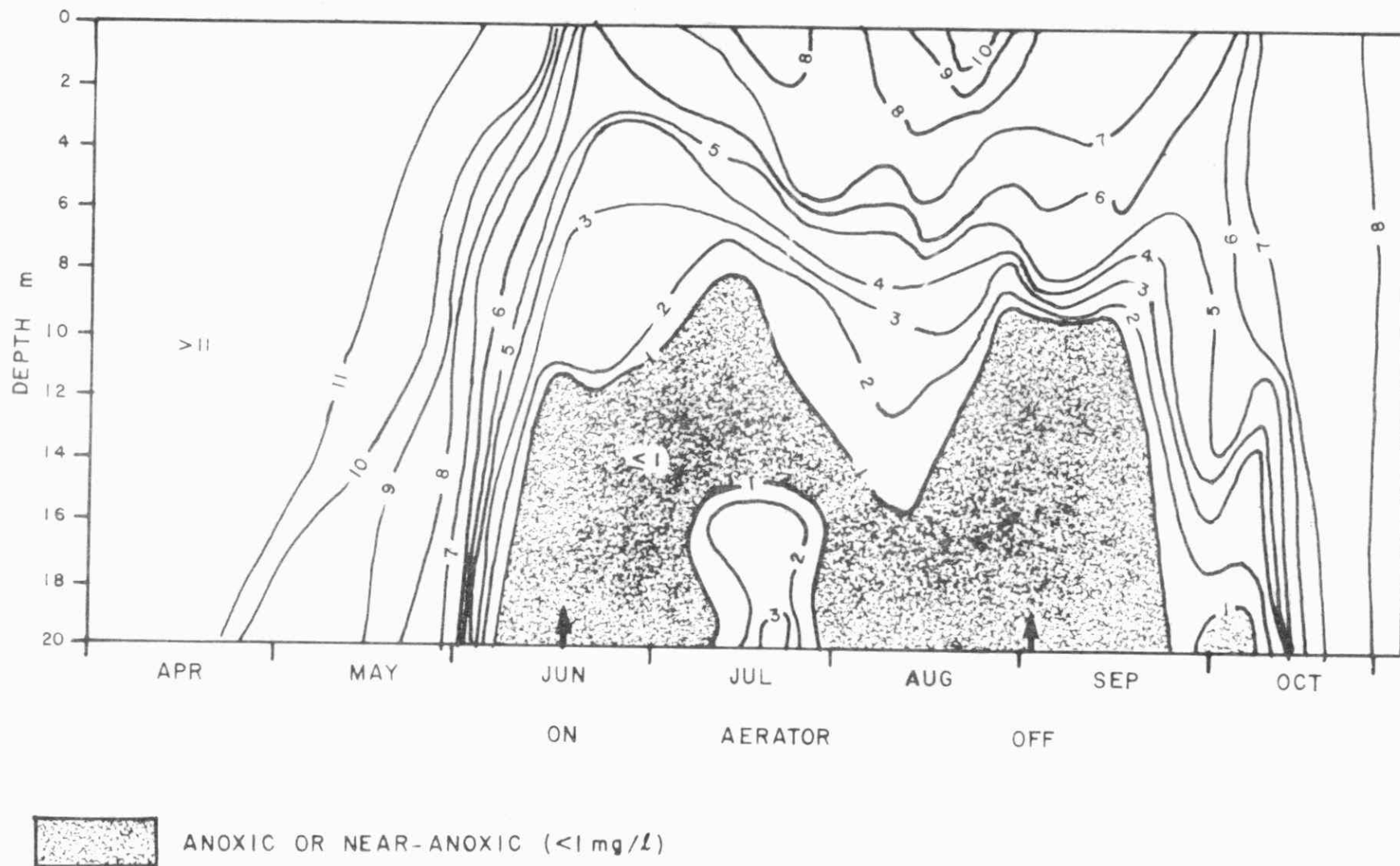
FIGURE 3c : DISSOLVED OXYGEN PROFILES (mg/ℓ). HAMILTON HARBOUR 1976 STATION 258.
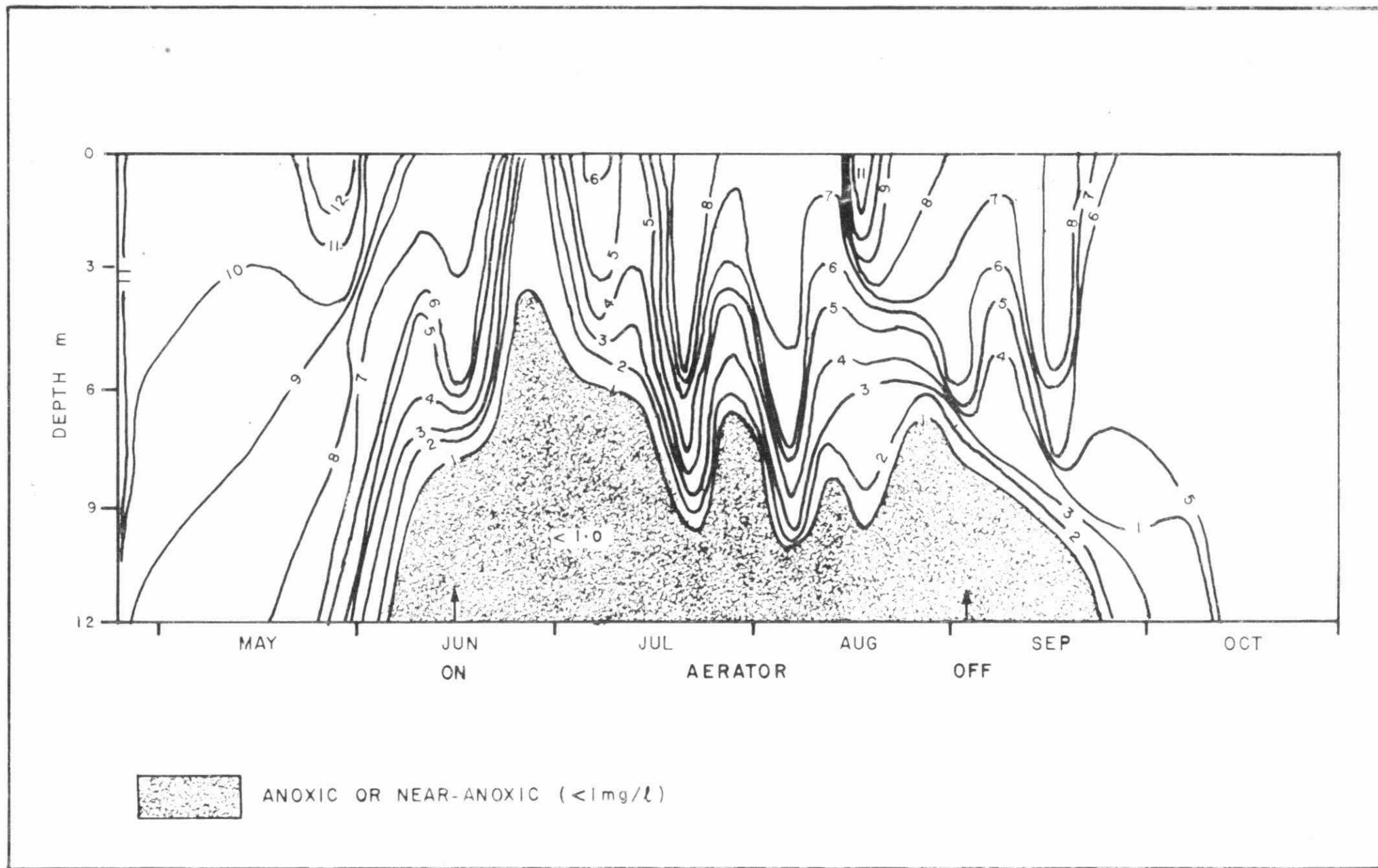
FIGURE 3d : DISSOLVED OXYGEN PROFILES (mg/ℓ), HAMILTON HARBOUR 1976 STATION 270
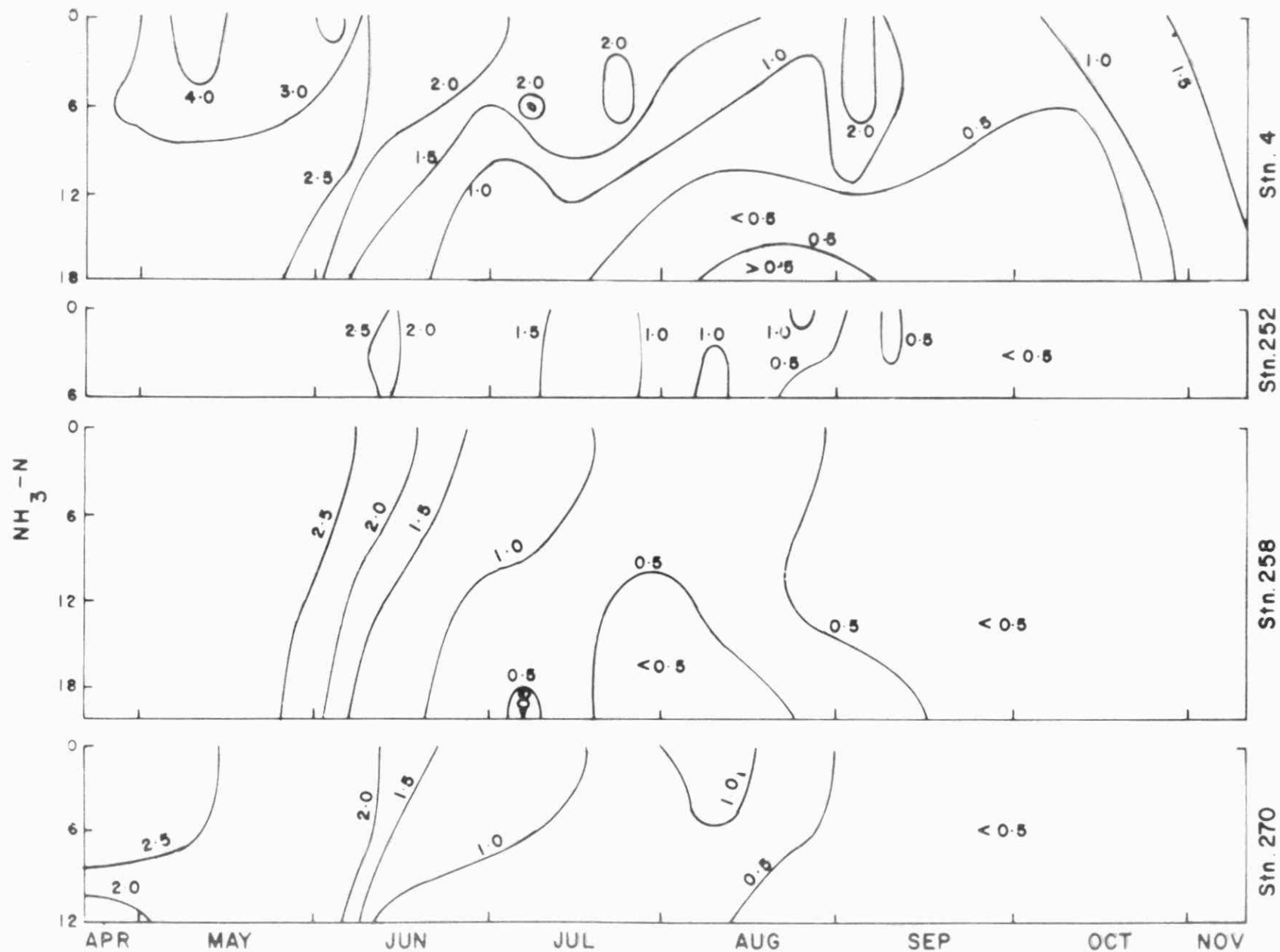
FIGURE 4 ISOPLETHS OF NH₃ (mg/l) AT MAJOR SAMPLING STATIONS HAMILTON HARBOUR 1976
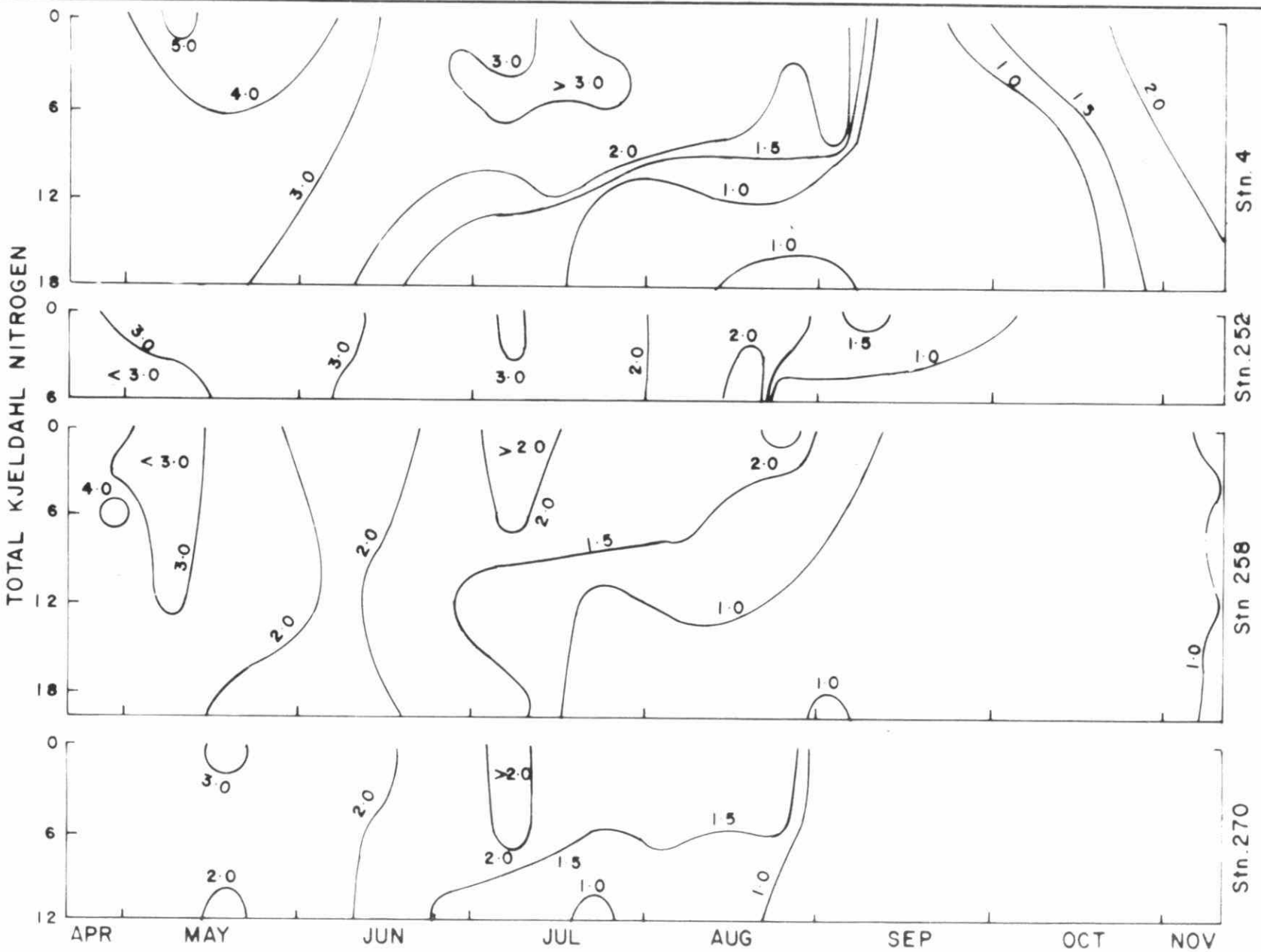
FIGURE 5 ISOPLETHS OF TOTAL KJELDAHL NITROGEN (mg/l) AT MAJOR SAMPLING STATIONS HAMILTON HARBOUR 1976
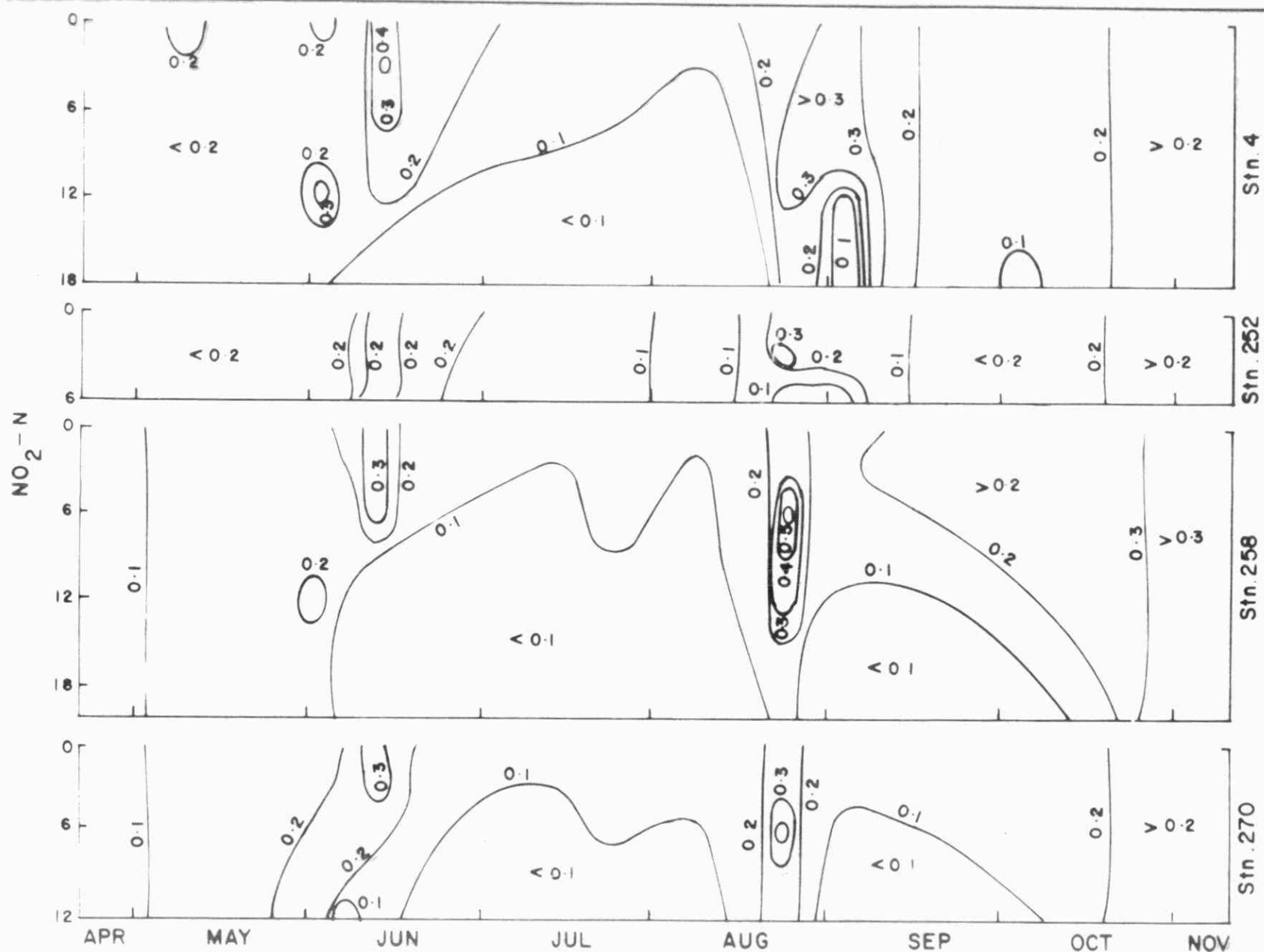
FIGURE 6 ISOPLETHS OF NITRITE mg/ℓ AT MAJOR SAMPLING STATIONS HAMILTON HARBOUR 1976
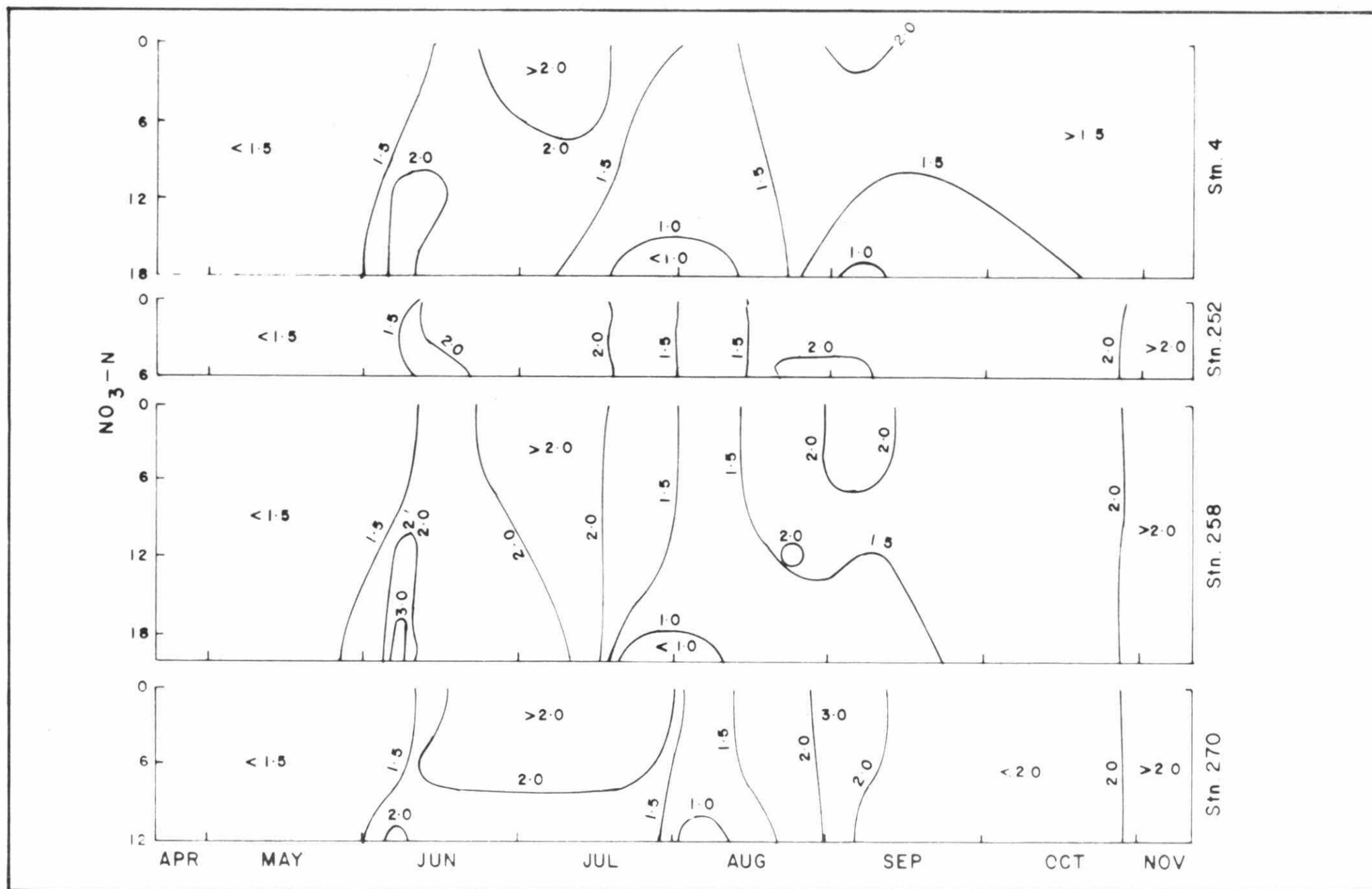
FIGURE 7 ISOPLETHS OF NITRATE (mg/ℓ) AT MAJOR SAMPLING STATIONS HAMILTON HARBOUR 1976
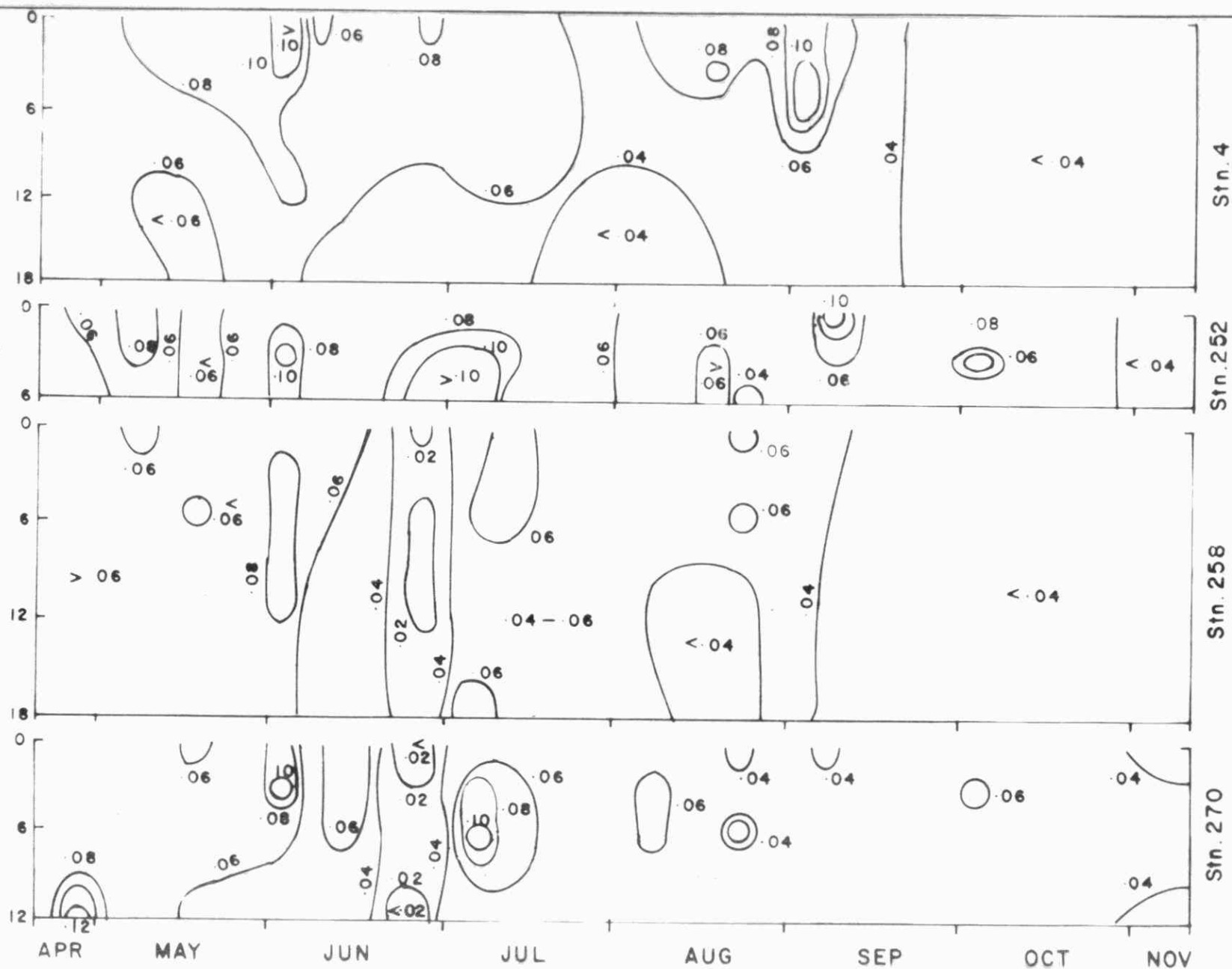
FIGURE 8 ISOPLETHS OF TOTAL PHOSPHORUS mg/ℓ AT MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976
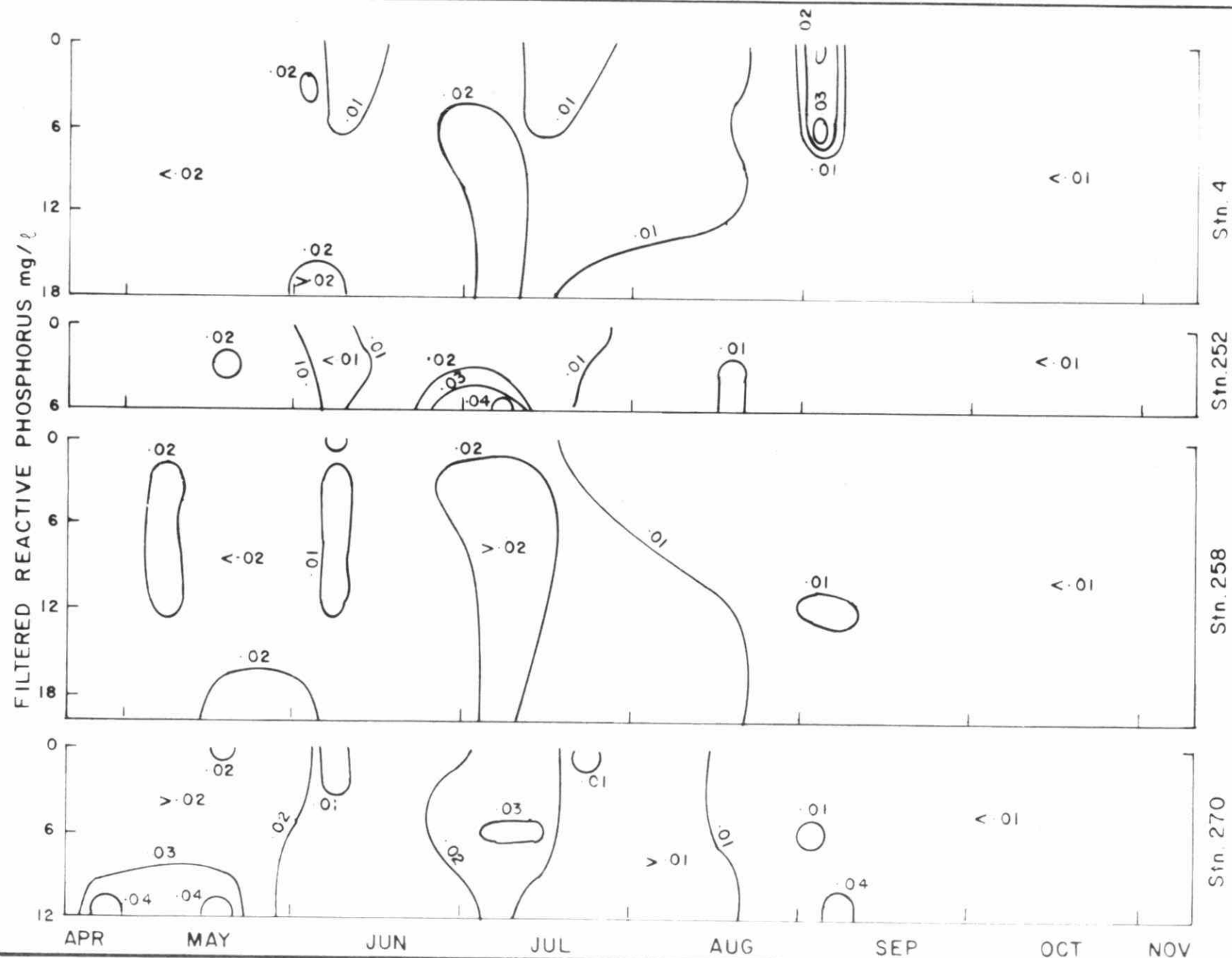
FIGURE 9   FILTERED REACTIVE PHOSPHORUS ISOPLETHS, AT MAJOR SAMPLING STATIONS, HAMILTON HARBOUR 1976
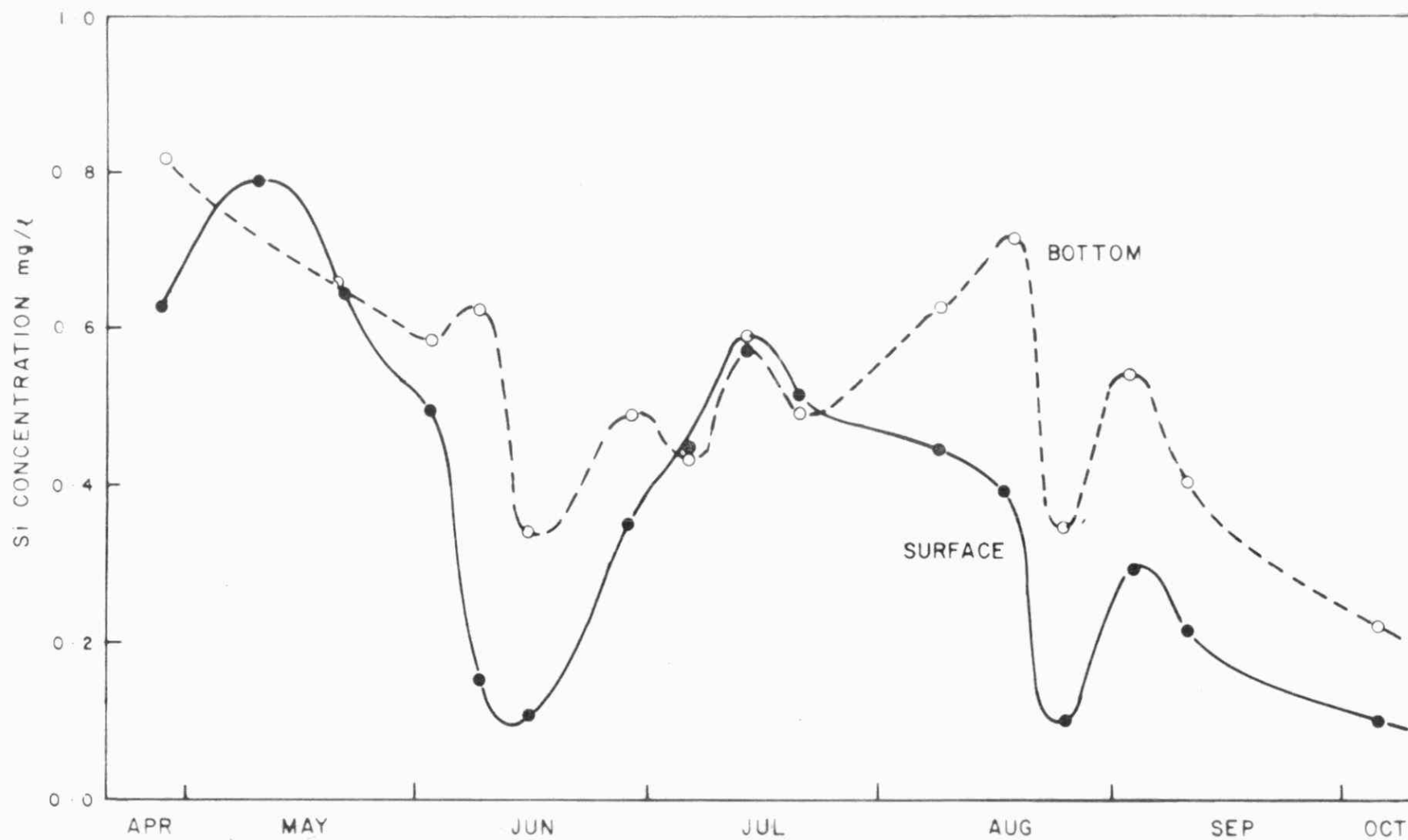
FIGURE 10 VARIATION OF SILICA WITH SAMPLING DATE, 1976 SURFACE AND BOTTOM MEANS

HAMILTON HARBOUR STUDY 1976

SECTION D

SEDIMENT CHEMISTRY

HAMILTON HARBOUR STUDY

SEDIMENT CHEMISTRY

SUMMARY

A SERIES OF CORE SAMPLES WAS TAKEN FROM HAMILTON HARBOUR IN JUNE 1976 AND SECTIONED INTO TOP, MID AND BOTTOM PORTIONS. HEAVY ENRICHMENT OF POLLUTANTS WAS OBSERVED AT MOST LOCATIONS WITH ENRICHMENT FACTORS (RATIO OF TOP TO BOTTOM CONCENTRATIONS) BEING 4 TO 140 AT STATION 258. AT STATIONS 4 AND 269, THE MOST HIGHLY ENRICHED MATERIAL WAS LOCATED SEVERAL CENTIMETERS BELOW THE SEDIMENT - WATER INTERFACE; IT IS SUGGESTED THAT THIS COULD BE DUE TO LAKE-HARBOUR EXCHANGE EFFECTS.

BY COMPARISON WITH OTHER GREAT LAKES AREAS, HAMILTON HARBOUR SEDIMENTS ARE MOST SEVERELY POLLUTED WITH RESPECT TO ZINC, LEAD AND CHROMIUM, AND TO A LESSER EXTENT, CADMIUM AND MERCURY. SPATIAL DISTRIBUTIONS OF THESE POLLUTANTS ARE SIMILAR TO THOSE OBSERVED IN PREVIOUS YEARS, WITH THE HIGHEST CONCENTRATIONS OCCURRING IN DEEP WATER AND ADJACENT TO THE OUTFALLS.

SULFIDE CONCENTRATIONS IN THE SEDIMENT WERE FAR LOWER IN 1976 THAN IN 1975. IT IS THOUGHT THAT THE INCREASED CONCENTRATION OF SULFUR OXIDIZING BACTERIA, AS STIMULATED BY THE ARTIFICIAL MIXING, IS RESPONSIBLE FOR THIS EFFECT.

FACTOR ANALYSIS OF THE RESULTS PRODUCED A SOMEWHAT MORE COMPLEX PATTERN THAN WAS OBSERVED IN 1975, PERHAPS BECAUSE OF THE LARGER NUMBER OF POINTS SAMPLED. TWO MAJOR FACTOR GROUPINGS WERE OBTAINED FOR THE DEEP WATER AREAS. ONE REPRESENTED THE CENTRAL AREA AND SOUTHEASTERN PART OF THE HARBOUR, AND THE OTHER REPRESENTED THE MID-DEPTH ZONE OF THE NORTH SHORE AND SOUTHWESTERN PART. OTHER FACTOR GROUPINGS

WERE OBTAINED WHICH RELATED THE SHALLOWEST AREAS, AS WELL AS
THE AREA MOST AFFECTED BY LAKEHARBOUR EXCHANGE. AS IN 1975,
THE AREAS CLOSEST TO THE MAJOR DISCHARGES REPRESENTED UNIQUE
FACTOR GROUPINGS.

IT IS SUGGESTED THAT SAMPLES OF HAMILTON HARBOUR SEDIMENT BE
FURTHER ANALYZED BY A CHEMICAL FRACTIONATION SCHEME, WHICH
WOULD LEND FURTHER INSIGHT INTO THE HEAVY METAL-PHOSPHORUS
RELATIONS, AS WELL AS THE BIOLOGICAL AVAILABILITY OF THE
CONTAMINANTS. IN ADDITION, THE CHEMISTRY OF THE SEDIMENT-
WATER INTERFACE SHOULD BE FURTHER INVESTIGATED BY ANALYZING
WATER SAMPLES FROM JUST ABOVE THE INTERFACE.

HAMILTON HARBOUR SEDIMENT CHEMISTRY

The intensive sediment surveys conducted in 1975 (MOE, 1977) showed the highest concentrations of nutrients and heavy metals to be located in the deep central part of the harbour and adjacent to the outfalls. The sediments were moderately to severely contaminated with nearly all heavy metals studied, and concentrations exceeded IJC dredging guidelines for open water disposal. Core samples indicated surface to bottom enrichment factors of 2-6.

Factor analysis of similarity coefficients obtained by the ratio matching method (MOE, 1975) indicated that sediment samples from the entire central and western deep portions of the harbour were strongly related. On the other hand, samples adjacent to industrial and municipal outfalls were unique and strongly influenced by these discharges. It was concluded that in order to reduce heavy metal concentrations throughout most of the harbour, a long period of natural sedimentation or a massive dredging program would be required.

On the basis of the 1975 findings, a series of sediment samples was collected in June 1976 by Phleger corer in the same manner as in 1975. The samples were frozen upon collection and stored in a freezer until sectioning was performed. All samples were sectioned at 5-7 cm from the sediment-water interface and additionally at the location of any color change; thus, most samples were divided into top, mid and bottom sections. In addition, the samples from the principal water chemistry sampling locations (4, 252, 258 and 270) were sectioned at approximately 10-12 cm intervals below the top 5 cm to provide a more detailed picture of pollutant-depth relationships. The locations sampled were altered according to recommendations made previously (MOE, 1977), as follows:

(a) More locations were sampled near the industrial shoreline, with two samples per location being taken to define spatial variabilities;

(b) Fewer locations were sampled in the laterally homogeneous central deep zone;

(c) Along the north shore, samples were collected from adjacent locations
of water depths less than 7 m (253-S, 257-S and 272-S) and water
depths greater than 10 m (253-D, 257-D and 272-D) for improved
definition of the zone of silty sediment in the shallow waters of
the north shore. The locations sampled are shown in Figure 1. All
samples were analyzed for lead, cadmium, mercury, iron, nickel,
chromium, zinc, total Kjeldahl nitrogen, total phosphorus and
chemical oxygen demand (COD). Samples from the more contaminated areas
were also analyzed for sulfide. Although the aqua regia digestion
method used in the analysis does not measure the total amount of
heavy metal present, it does extract elements present in adsorbed
positions, in solution in the interstitial water, and in precipitated
oxides, hydroxides, carbonates and sulfides as well as the organic
material. This represents the fraction of elements which are most
able to migrate in the upper part of the sediment (Mothersill,
1977) as well as the probable forms of most pollutant material.

Results

Visual descriptions of all sections obtained in 1976 are given in Table
1. Other than at Station 230, the sections of duplicate samples taken
along the industrial shoreline were similar to each other, except that
the lowest portion was not always obtained in both samples due to variations
in the depth of corer penetration. Thus, the descriptions of these
cores are combined, with the ranges in section length indicating the
variation between the duplicate samples.

The distribution of various types of surficial sediment is very similar
to that observed in 1975. Organic muds were found at all deep water and
industrial shore locations except for 257-D on the edge of the deep area
in the north, where 11 cm of brown silt overlaid a 15 cm thick organic
mud layer. Sand was found at Station 1030 on the Lake Ontario side of
the Burlington Ship Canal while silt or sandy silt was found at all
shallow locations along the north shore and at the far western end of
the harbour. Sandy silt was also found at Station 269 near the Burlington
Ship Canal and a silty organic composite at Station 255 about 1 km south
of the canal.

Most mid-portions of sub-surface layers were similar in appearance to the surface samples, while the bottom portions of cores where sufficient corer penetration occurred were generally brown silt or sandy silt. When only two layers were obtained, the lower layer was designated as mid or bottom according to its appearance as well as similarity to other samples according to the ratio matching analysis discussed later.

Unusual layering of sediments was observed at locations 20 (two samples) and 230 (one of two samples) in the southeast corner of the harbour. At these points the lowest layer collected was black organic mud similar to the surface material, underlying a silty layer similar to bottom material found elsewhere. Chemical analysis corroborated the similarity of the lowest layer to the top or near-top portions.

Profiles of pollutant concentration against depth were measured in more detail at stations 4, 252, 258 and 270 in 1976, by sectioning the cores into 4 or 5 sections, each 5-12 cm thick. The results are shown in Figure 2. In general, similar depth distributions were obtained for different pollutants measured at the same station, but differently shaped depth distributions were found for the four locations. Station 4 presented an unusual depth distribution, with concentrations in the second layer being two to three times those of the top layer. Reduced top layer concentrations were seen at Station 269 and to a lesser extent at Station 255 but not elsewhere (except for an occasional parameter). This suggests that this could be an effect of harbour-lake exchange but more work would be needed to verify this.

For the other three stations, location 258 showed the greatest enrichment factors from surface to bottom (4 to 140). These are all higher than the average enrichment factors calculated from top and bottom mean 1976 data (Table 2) which are included below:

Enrichment Factors

Parameter	Average	Station 258	Station 252
Pb	9.3	34.	13.
Cd	4.5	4.9	12.
Ni	2.8	4.3	2.1
Cr	6.0	18.	4.3
Zn	9.6	48.	19.
Hg	8.4	140.	20.
Fe	3.5	8.1	1.4
TKN	1.7	5.6	0.9
Total P	3.0	6.1	3.1
COD	3.0	11.6	1.5

This emphasizes the tendency for fine particles containing the highest concentration of contaminants to drift to the deepest portions of the harbour. Data for Station 252 indicate severe enrichment for Pb, Cd, Zn and Hg of relatively recent origin (as most of the enrichment is within the top 5 cm at this location).

It is significant that those metals with average enrichment factors greather than 5 (Pb, Zn, Cr, Hg) are those with the largest proportion of excessively polluted samples. Chromium, zinc and lead (as well as iron) are the metals which are discharged in the greatest quantities to the harbour, according to 1975 data (MOE, 1977). It is also significant that all these enrichment factors, except possibly iron, are greater than those observed with cores taken in June and August 1975 (MOE, 1977) and most especially for lead and mercury. These are also the metals which tended to have higher concentrations in the May 1975 dredge samples compared to the 1975 cores. These observations emphasize the considerable enrichment of pollutant that occurs in the top few centimetres of Hamilton Harbour sediments, and indicate that only the topmost material should be taken for analysis in order to give the most accurate picture of recent sediment pollution in Hamilton Harbour.

This conclusion is substantiated by comparison of the average concentrations of the top and mid portions of the 1976 sediment samples to the 1975 results. For most parameters, the mean of the 1976 top portions is similar to 1975 dredge results, while the mean of the 1976 mid-portions is similar to the 1975 core top portions. Dredge means for mercury (and to a lesser extent zinc and cadmium) are even higher than the 1976 mean, suggesting that the most highly enriched material may be within even less than 5 cm from the sediment-water interface. This is difficult to prove, as factors such as depth of dredge penetration or disturbance of the surface layers during core penetration may also play a role.

Mean values for sulfide are given in Table 2, and contours plotted for surface portions of the cores in Figure 3. The mid-portion for most samples having a surface mean of 0.02 mg/g or less, was not analyzed. Two values are given for the surface sulfide mean: one represents all samples and second represents those for which the mid-portion was not analyzed for sulfide. The second value is larger and is more precisely comparable to the mid-portion figure for the purpose of indicating sediment sulfide variation with depth. Negligible sulfide concentration was found in all samples from the shallow north shore and west end areas, as well as a zone in the east end influenced by lake effects. These locations correspond to points at which the sediment-water interface is aerobic on a year-round basis.

These observed sulfide values are the most significant change found between the 1975 and 1976 sediment samples. The top portions of 1975 cores averaged 367 μg/g, with a maximum value of 2600 μg/g located at station 262. The maximum 1976 result was 16 μg/g, also at station 262. The large analytical difference is supported by the lack of hydrogen sulfide odor in the 1976 samples, compared to the 1975 samples. It appears as though the artificial mixing program has produced this beneficial effect, presumably through stimulation of the sulfur oxidizing bacteria (Section A, Artificial Mixing). Geometric means of sulfur oxidizers ranged from 1.3×10^5 to 3.4×10^5 counts/100 ml at the bottom levels of four major sampling stations in 1976, compared to a range of 1.1×10^3 to 8.5×10^3 counts/100 ml in 1975. As sulfide is a mobile

substance, easily subject to dissolution and migration in the inter-
stitial waters, large changes can occur rapidly. Part of the decrease
should therefore be considered a seasonal effect, as the 1976 samples
were collected in June, before extensive hypolimnetic anoxia had occurred,
while the 1975 samples were collected in August.

Heavy Metals

As was done with the 1975 data (MOE, 1977), the concentrations of the
top portions of the 1976 sediment cores were compared to values character-
istic of "elevated" and "excessive" heavy metal concentrations of Great
Lakes sediments (Fitchko and Hutchinson, 1975). These authors considered
sediment heavy metal concentrations of more than the mean plus two
standard deviations of the concentrations from uncontaminated Great
Lakes river mouth areas to indicate "elevated" values and concentrations
more than 5 times these values to indicate "excessive" values. Figures
4-9 indicate the areas of elevated concentrations for Zn, Cd, Pb, Cr, Ni
and Hg for 1976. Zn, Pb and Cr present similar distributions of excessive
concentrations to those observed in 1975 with the entire harbour exhibiting
excessive concentrations except the shallow northern, northeastern and
far western areas. Cadmium shows excessive concentrations in most of
the deep area and a southeastern portion of the harbour (the dashed line
in Figure 4 shows an area of deduced excessive concentration which was
not demonstrated due to lack of sampling). This represents a significant
change from 1975 conditions and is probably due to the method of core
sectioning used in 1975 as discussed earlier. Nickel presents elevated
concentrations except in the shallow (non-polluted) zones, and mercury
presents excessive concentrations in the deep water and southeastern
zone (the dashed line in Figure 8 has the same significance as in Figure
4), and non-polluted concentrations in the shallowest northern area.
The nickel and mercury distributions are both similar to 1975 despite
the change in core sectioning method used in 1976.

Factor Analysis of 1976 Sediment Data

The results from the top portions of the 1976 cores were processed by
factor analysis of the similarity coefficients as done previously with
the 1975 data (MOE, 1977). The results are shown in Figure 10.

The 1976 data produced a factor pattern similar to, but somewhat more complex than the 1975 data. The principal factor relating all deep water areas, as observed in 1975, was split into two groups: the first contained the deepest central areas as well as the southeastern part of the harbour, as far east as Station 230, and the second contained the southwestern zone as well as the northern points sampled at depths greater than 10 m. Factor loadings (not presented) indicated some inter-relation between these two main groups.

The effect of Lake Ontario was noticed with relationships involving Stations 1030 and 269 at opposite ends of the Burlington Ship Canal. Station 1030 was related to one group of stations comprising stations 269, 255, 266 and 271, and to another group containing stations 272-S and 264. The first group encompasses a zone of silty sediments similar to that identified in June 1975, and the second group comprises sands taken from very shallow water depths. It is difficult to assess the reason for the appearance of these two separate groups except that one represents slightly deeper water and finer grained sediments (silt) than the other.

As in 1975, samples taken from points nearest the industrial and municipal outfalls present unique factors, suggesting that large amounts of pollutants discharged in the vicinity are quickly sedimented. These shallow zones were again used to indicate areas which are more affected by waste discharges (Table 3). The zones with highest pollutant concentrations are Randles Reef (Pb, Cd, Hg, Zn, Fe), Ottawa Street Slip (Pb, Ni, Cr, Zn, Fe), and the Hamilton Sewage Treatment Plant (Ni, Cr). These areas are similar to 1975. Two additional locations sampled in 1976 near the industrial shoreline did not show signs of unusual contamination: these were 266 (off the north end of Stelco) and 105 (near the Wellington Street Slip).

A separate factor describing shallow north shore sediments at locations 253-S and 257-S was observed. This was as expected from previous data, and reflects the fact that these sediments are generally exposed to oxygenated epilimnetic water. The shallowest points sampled, 272-S and

264, represent another factor as mentioned earlier, perhaps related to their sandy nature.

As suggested in 1975, a zone of conflicting transport processes was detected at Station 255 in 1976. The sample was related to both the principal factor and shallower areas. The mixed nature of this sample was suggested by its description as a silt-organic composite (Table 1).

Factor analysis was also performed on the bottom portions of the core samples. Although association between some west end areas was suggested, no factor indicating a meaningful relationship was found. This suggests that at least some of the cores did not penetrate deeply enough to obtain sediment deposited before industrial development occurred.

R-Mode Factor Analysis

In order to assess which elements behaved similarly during sedimentation, R-mode factor analysis (between parameters) was performed on the top portions of the cores. The results are given in Table 4. As in 1975, transition metals (Fe, Cr and Ni) were associated in one factor and post-transition metals (Zn, Pb, Cd and Hg) were associated in a separate factor. This confirms consistency of data and analytical techniques between years. Nutrients (N and P) were related in a third factor. Organic matter, as represented by COD, was most strongly related to transition metals. This is similar to the result observed in 1975, although the weaker relationship to post-transition metals found in 1975 was not evident.

Discussion

As discussed in the previous sediment report (MOE, 1977, Section C), the generic similarities exhibited by the sediments of the deepest part of the harbour indicate that common mechanisms are important in transporting pollutants from the zones adjacent to the discharges towards the deep water areas. The central and southeastern deep zones appear to be slightly more affected by the discharges, compared to the deeper areas adjacent to the north shore and west end.

Many studies have established the importance of the sediment-water interface in controlling the chemistry and biology of natural waters. Much of the chemical changes occurring at the interface are controlled by redox conditions. Reducing conditions brought about by hypolimnetic anoxia cause the reduction of ferric oxides to the ferrous state, with consequent release of adsorbed phosphorus to the water column. As a result, the hypolimnetic waters of eutrophic lakes develop a summer phosphorus maximum related to the period of anoxia. However, in Hamilton Harbour, although anoxia did occur, increased levels of dissolved phosphorus were not observed except in one case. Harris (1977) observed one instance of very high soluble phosphorus at Station 270 in August 1976, but MOE data for 1976 (Section C, water quality update) did not indicate any values above 0.1 mg/l. At present, the source of the observed temporal variations of hypolimnetic phosphorus (total or soluble) is not known.

The phosphorus cycle in Hamilton Harbour has been discussed previously with regard to iron-phosphorus relationships existing within the water column (MOE, 1974, Section E). Although it was felt that soluble phosphorus values were influenced by the presence of condensed phosphates, organic phosphates, metal complexes and finely divided particulate matter, no explanation was offered with regard to the lack of phosphorus release under hypolimnetic anoxia. Data obtained in 1975 (MOE, 1977, Sections A & C) suggested that the control of phosphorus release from sediment may be more complicated than the simple iron-phosphorus-dissolved oxygen system. This was substantiated by 1976 data, which indicated a strong relationship between total phosphorus and total Kjeldahl nitrogen in the surface portion of the cores. Weaker relationships with cadmium and chromium were also evident. In the following discussion, sediment-water relationships are further reviewed, first with respect to heavy metals and then to phosphorus. Observations in the scientific literature are related to events occurring in Hamilton Harbour and proposals are made for further study.

Similar to the sediment phosphorus studies discussed later, various extraction schemes have been applied to heavy metal fractionation studies of sediments. Partial extraction schemes are favored over determination of total metals as the metals present in discrete relatively inert phases are not readily exchangeable and interest is centred upon the availability of trace metals for metabolic processes. As the sediments provide a vast reservoir of heavy metals which have been deposited in recent decades, and it has been suggested that zinc toxicity is important in controlling the Hamilton Harbour biota, studies of sediment-water interrelationships should be an important part of any ongoing study.

In a study of heavy metals in sediments, Malo (1977) used four partial extraction procedures: 0.3 M HCl, citrate-dithionite (CD) buffered at pH3, citrate-dithionite-bicarbonate (CDB) at pH7, and acetic acid-hydroxylamine. Despite the successful use demonstrated by Williams et al (1971a) for Fe, Al and Mn, the CDB procedure, which is frequently applied to phosphorus studies, was found to be unacceptable for many metals due to low recovery levels possibly related to readsorption or co-precipitation of metals at the high pH used, as well as the number of reagents which led to operational difficulties associated with high dissolved solids in the atomic absorption analysis. The pH3 CD and acetic acid-hydroxylamine procedures suffered from the latter problem and the 0.3 M HCl procedure was selected as the most successful. The acetic acid-hydroxylamine procedure was used by Lahann (1976) and did give significant extractions of Fe, Mn and Zn. Oxalic acid-ammonium oxalate extraction as used by Williams et al (1971a) recovered similar amounts of Fe and larger amounts of Mn than CDB, apparently extracting the proportions of these metals associated with short-range order amorphous hydroxides; presumably other trace metals associated with this phase are also extracted. This extraction procedure is performed at a lower pH than CDB, thus precluding the re-precipitation problems encountered with the latter reagent.

A widely used partial extraction procedure for heavy metals is ammonium pyrrolidine dithiocarbamate-methyl isobutyl ketone (APDC-MIBK) (for example, Mothersill, 1977; Lu and Chen, 1977; Helz, Huggett and Hill, 1975; Gibbs, 1973). The principle of this matter is that APDC will chelate the metals from adsorbed (non-occluded) positions or metals that are dissolved in the interstitial water. Metals associated with organic matter are also extracted. These complexes are extracted into a smaller volume of MIBK, which can be separated from the aqueous phase. The MIBK is then evaporated and the residue taken up in 30% HCl for atomic absorption analysis. In this manner a clean extract is obtained without the high solids associated with citrate-bicarbonate procedures. The procedure, however, suffers from the drawback that the amounts of Fe, Mn, Zn and Cu are pH-dependent (Mothersill, 1977). In addition, the fractionation procedure of Gibbs (1973) suggests that adsorbed or biologically associated metals are not extracted. It is likely that tests of several procedures would be required to deduce a reliable extraction scheme.

As with 1975 data, factor analysis of the 1976 sediment top portions indicates a division of the metals into factors represented by transition and post-transition metals. An explanation was offered based upon the relative stabilities of transition and post-transition metals complexes, as predicted by crystal-field stabilization theory (MOE, 1977). Forstner (1976) observed a similar separation of transition and post-transition metals in a study of Rhine River sediments. The transition metals were mainly associated in the detrital fraction of the sediment; in contrast, zinc, lead and cadmium exhibited very low contents associated with detrital forms. Zinc and cadmium were mainly associated with carbonate forms, while lead was mainly associated with hydroxide forms. Copper and chromium were also somewhat associated with hydroxides. While the same mechanisms may not be operating in Hamilton Harbour, the division into detrital and non-detrital fractions is interesting and warrants further investigation.

Forstner (1976) also summarized the chemical bonding of trace metals in sediments in several forms as follows:

(a)   Inert deposition in natural rocks (discrete minerals);

(b)   Precipitation as hydroxides, carbonates, sulphides and phosphates under natural alkalinity;

(c)   Sorption and cation exchange on fine-grained substances such as MnO_2, humic acid, hydrous Fe oxides and clay;

(d)   Dissolved organic complexes with ligands such as fulvic acids; and

(e)   Co-precipitation of heavy metals with carbonates and hydroxides.

Categorization of actual samples is generally done on the basis of observed association of one element with another; however, as many different schemes of association appear to occur in the literature as there are investigators. Certainly, the distinction of some of the above forms is extremely difficult. For this reason, Gibbs (1973) combined the precipitated and co-precipitated fractions above in an otherwise similar scheme. Sorption and co-precipitation (for example, on or with hydrated Fe and Mn oxides), or fulvic acid complexation, may well explain observed inter-associations of sediment heavy metals.

Another factor governing heavy metal transport and sedimentation is grain-size. In general, most heavy metals are associated with fine grained materials, such as clays. Forstner (1976) cites an example for cadmium, which was found mainly in the 0.2-0.63 μm (clay) fraction in Main and Rhine river sediments.

The chemistry of the interstitial water also plays an important role in heavy metal transport. Concentration of dissolved oxygen and sulphide, and their control by redox potential are important. Patrick, Gambrell and Khalid (1977) have reviewed the reactions of heavy metals in dredged sediments and stressed two opposing viewpoints. One is that under reducing conditions, sulfide precipitation will immobilize heavy metals,

while these will be released when sulfide is oxidized. The opposite is that the heavy metals will be more soluble under reducing conditions as a result of reduction of hydrated ferric and manganese oxides, which tend to adsorb or coprecipitate many metal oxides. In marine systems, heavy metals are frequently released into solution due to sulfide oxidation and complexation with ligands (such as Cl^-) found in abundance in sea water (Lu and Chen, 1977). However, in fresh water, most studies cited by Patrick, Gambrell and Khalid (1977) indicate decreased heavy metal solubility under oxidizing conditions. Complexation with organic ligands may also be important. The same authors also indicate the possibility of release of heavy metals from insoluble humic materials when the latter are broken down under oxidizing conditions, but concede that such release would occur only where a reduced sediment is exposed to oxidizing conditions for a considerable period of time. Although this condition could potentially occur under conditions of artificial mixing in Hamilton Harbour, it is most likely that adsorption by the abundant hydrous ferric oxides would prevent such heavy metal release.

As is the case with heavy metals, sediment phosphorus has been grouped into various fractions. Williams et al (1971a) divided sediment P into four categories:

(a) Non-occluded P, or orthophosphate sorbed on the surfaces of sediment particles;

(b) Occluded P, or orthophosphate ions held within the crystalline matrices of sediment particles;

(c) Discrete P, or P present in definite minerals such as variscite ($AlPO_4 \cdot 2H_2O$) or strengite ($FePO_4 \cdot 2H_2O$); and

(d) Organic P.

Efforts to differentiate the nature of sediment P in past studies have mainly revolved around inorganic P fractionation schemes originally developed for soils by Chang and Jackson (1957) and since modified for calcareous and non-calcareous lake sediments, in a series of studies on

Wisconsin Lakes by Syers, Williams and co-workers (Syers, Harris and Armstrong, 1973; Williams et al, 1971a, 1971b, 1971c). In addition, the results of heavy metal and P extractions should correlate better with biological availability than results obtained from strong acid digestions of sediments, which tend to destroy the clay lattice (Lahann, 1976). Phosphorus and heavy metal adsorption and release studies have also been performed (for example Ku, 1975; Lu and Chen, 1977) and attempts to model the equilibria therein have been performed.

The usual inorganic P fractionation scheme is reviewed by Syers, Harris and Armstrong (1973). The extractions involved are as follows:

(a) NH_4Cl extraction, removes dissolved P in interstitial water and weekly sorbed phosphate ions from the sediment surface;

(b) NH_4F, followed by; (c) NaOH. It was originally thought the fluoride extraction removes Al-held P and Na OH extraction removes non-occluded Fe-held P. However, more recent evidence (Syers, Harris and Armstrong, 1973; Williams et al, 1971b) indicates that NH_4F is not selective for Al-bound P in many materials and can therefore not be used to distinguish between Al-held and Fe-held P. Results were further complicated by resorption of released P during the NH_4F extraction. This resorbed P was released in the subsequent NaOH extraction. Furthermore, in the case of calcareous sediments, CaF_2 is formed during the fluoride extraction, and takes up released P, which is not released again until the subsequent HCl extraction (Williams et al, 1971c).

(d) Reductant soluble P. This fraction has been obtained by extraction with either citrate-dithionite-bicarbonate (CDD) or ammonium oxalate reagents in different studies (Williams et al, 1971a, 1971b). Results of Fe extraction by these reagents indicate that either reagent attacks the same form of Fe. Phosphorus released in this extraction was postulated by Williams to be contained in an amorphous

short-range order Fe-inorganic P complex. Because this complex was evenly distributed through the sediments, with a strong Fe-P relationship persisting below the microzone, they felt that the Fe may be in the ferrous form; however, as redox kinetics are generally slow, it is possible that this phase represents a complex containing both ferrous and ferric iron.

(e) HCl extraction. This removes Ca-bound P (hydroxylapatite). In non-calcareous sediments this generally represents a small fraction of inorganic P, perhaps because of the slow kinetics of Ca phosphate formation.

(f) Ignition at 550-600°C followed by HCl extraction removes organic P which should represent a significant fraction of the total P in the sediments of any area receiving large organic loadings.

(g) Na_2CO_3 fusion. This extracts residual inorganic phosphorus, which, because of its refractory nature is not available to compete in the phosphorus cycle of the water body. Many of the fractionation studies have omitted both steps (f) and (g).

It is proposed that a limited fractionation scheme be applied to a few samples of Hamilton Harbour sediment, in order to understand more about the heavy metal-phosphorus relations existing therein, as well as the biological availability of the various contaminants. Hamilton Harbour sediments contain a significant amount of calcareous material (minerological analysis (Mudroch, 1974) indicated 8% dolomite; average calcium content of 1975 samples was 48-56 mg/g). Therefore it is not expected that the NH_4F extraction would provide useful results. A scheme consisting of extractions by NaOH (Al- and Fe-bound nonoccluded P), oxalate or CDB (Al-and Fe-bound occluded P) and HCl (Ca-bound P), and ignition plus HCl (organic P) would be adequate. Optionally, an NH_4Cl extraction could also be included. The extracts should be analyzed for iron, aluminum, cadmium, chromium, manganese, zinc and lead to elucidate possible associations of these metals with P, as well as the biological availability of these metals.

The proportions of phosphorus and heavy metals recovered in NaOH and CDB or oxalate extractions would represent the amounts most readily available biologically, and may represent more ecologically significant figures than the results now obtained by aqua regia digestion. The NaOH fraction is more available than the reductant soluble fraction. If much of the iron in the harbour sediments is an amorphous gelatinous oxide precipitate, as is generally thought, high extractions of iron should be obtained in these steps. However, Williams et al (1971a) stated that these short-range order complexes constitute very mobile systems which can respond sensitively to changes in the pH and Eh of the sediment- water interface. Such complexes should therefore release iron and phosphorus to the hypolimnion under anoxic conditions; thus in Hamilton Harbour, either these complexes must be absent or some other factor must be affecting their mobility, because of the absence of such anoxic releases. On the other hand, aluminum, which is likely bound in the clay (illite) fractions, should not be significantly extracted, as was observed by Lahann (1976). Williams et al (1971a) found that less than 10% of aluminum was extractable by oxalate, but the aluminum which was extracted was associated with organic P. The results of oxalate or CDB extraction of Zn in particular should be interesting in view of the suspected Zn toxicity limitation to algal growth in Hamilton Harbour.

Owing to the slowness of the Ca-phosphate precipitation reactions it is not likely that much of the P would exist in the HCl extractable fraction. However, P in this fraction would not be readily released under hypolim-netic anoxia and a large extraction of P in this fraction could explain the observed lack of phosphorus release.

As Hamilton Harbour sediments contain a very high concentration of organic muds, much of the phosphorus might be found in the ignition-HCl fraction. Not as much is known about the mobility of this fraction although evidence exists for its association with oxalate-extractable Al. A high concentration of P here would indicate the desirability of further studies in this field.

Initially only a single location need be studied; it is suggested that Station 258 be used as it contains the highest concentration of most contaminants except for localized areas near discharges.

Wildung, Schmidt and Routson (1977) observed a seasonal dependence of extractable P parameters: NaOH and reductant-soluble P decreased from May to July, which they related to biological productivity and demand for phosphorus in surface water. Deposition and mineralization of the detritus in the fall contributed to a gradual increase in several fractions from August to November. A seasonal study in Hamilton Harbour on the basis of a monthly sample would prove interesting in relating to the biological cycles. It would be necessary to establish that observed differences were greater than spatial differences, which can be quite considerable as observed with core samples from the industrial shoreline.

Supplementary to such a seasonal study, a more detailed study of the sediment-water interface is desirable. Complimentary studies of selective extraction procedures along with experimental measurement of nutrient and heavy metal uptake and release under varying chemical and biological conditions could be undertaken. It would be valuable to co-ordinate such studies with those on sediment oxygen demand and methane production which are presently underway.

The chemistry of the water next to the interface should also be investigated more thoroughly. In order to collect a water sample from just above the sediment-water interface, a special sampler such as that developed by Sullivan (1967) could be used. This consists of a bottle enclosed in a wire mesh cage and provided with a valve which automatically opens at the bottom and is closed again on ascent. Samples should be collected bi-weekly and analyzed for dissloved oxygen, nutrients and heavy metals. It would be hoped to relate the results from this program to any seasonal changes in sediment chemistry as well as the overall harbour chemistry and biology and effects of the artificial mixing program.

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TABLE 1

DESCRIPTION OF 1976 HAMILTON HARBOUR SEDIMENT
SAMPLES

Station	Water depth m	Top Portion	Mid Portion	Bottom Portion
1030	12.2	4 cm brown sand	–	8 cm light brown sand
269	15.2	6 cm brown sandy silt	25 cm dark brown sand-organic composite	–
4	19.8	6 cm black organic	10 cm brown organic; 25 cm dark brown organic	11 cm sandy silt
267	14.0	6 cm black organic	42 cm black organic	18 cm sandy silt
20	11.1	5 cm black organic	18 cm black organic	8 cm light brown silt; 5 cm black organic
230	9.1	5 cm black organic	25 cm black organic	5 cm brown silt; 9 cm black organic
230	9.1	5 cm black organic	8 cm silt-organic composite	20 cm black organic
268	3.8	6 cm black organic	20 cm black organic	3 cm brown silt
2	4.6	5 cm black organic	35 cm black organic	–
256	15.2	5 cm black organic	28-35 cm black organic	14 cm brown silt (one sample only)
255	16.2	5 cm dark brown silt-organic composite	33 cm dark brown silt-organic composite	–
266	15.1	5 cm dark brown organic	23-33 cm dark brown organic	–
259	21.3	5 cm black organic	30-48 cm black organic	6-25 cm brown silt
262	10.5	5 cm black organic	30 cm black organic	8 cm light brown silt (one sample only)
130	11.9	6 cm brown organic	23 cm brown organic	–
15	12.2	6 cm brown silt	22 cm dark brown organic	10 cm light brown silt (one sample only)

Station	Water depth m	Top Portion	Mid Portion	Bottom Portion
270	14.3	7 cm dark brown organic	25 cm dark brown organic	18 cm dark brown organic
271	8.8	5 cm brown organic silt	40 cm brown organic silt	–
264	3.7	8 cm brown sand	–	–
252		5 cm brown silt	23 cm brown silt	15 cm light brown silt
253-S	6.4	5 cm brown silt	–	19 cm brown organic silt
253-D	12.2	5 cm dark brown organic	38 cm dark brown organic	–
257-S	6.7	7 cm brown silt	18 cm brown organic silt composite	6 cm light brown sandy silt
257-D	14.3	5 cm brown silt	6 cm brown silt; 15 cm brown organic	10 cm light brown sandy silt
272-S	3.0	5 cm light brown sandy silt	13 cm light brown sandy silt	–
272-D	15.2	6 cm dark brown organic	23 cm dark brown organic	–
258	23.8	6 cm dark brown organic	30 cm dark brown organic	16 cm light brown silt

TABLE 2

MEAN RESULTS OF HAMILTON HARBOUR SEDIMENT ANALYSES, 1976

| | Top Portion | | Mid Portion | | Bottom Portion | | Great Lakes Concentration Comparative Values | |
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Elevated	Excessive
Pb	260	220	210	250	28	34	28	140
Cd	5.0	3.8	3.9	3.1	1.1	1.9	1.7	8.5
Ni	39	26	29	15	14	7	28	142
Cr	200	190	130	120	34	45	16	82
Zn	2010	1780	1550	1940	210	260	118	591
Hg	0.42	0.36	0.31	0.31	0.05	0.10	0.12	0.58
Fe (mg/g)	70	64	56	49	20	8	-	-
TKN (mg/g)	2.7	1.7	2.5	1.5	1.6	1.5	-	-
Total P (mg/g)	2.4	1.5	1.7	0.8	0.8	0.3	-	-
COD (mg/g)	140	100	110	80	47	50	-	-
Sulfide	2.6	3.7						
	(4,7)*	(4.6)*	3.4	5.1	-	-	-	-
	(4.7)*	(4.6)*						

Note: All analyses are in ppm (μg/g), unless otherwise stated.
"Top" refers to the top 5 to 7 cm of each core.
"Mid" refers to sediment below 5 to 7 cm, to the color change where present.
"Bottom" refers to sediment below the color change.
Great lakes concentration comparative values are based on (mean + 2 S.D.) and
5 (mean + 2 S.D.) of heavy metal concentrations found in the sediments of 25 relatively
undeveloped river-mouth locations (Fitchko and Hutchinson, 1975).
*   Mean of stations at which "mid" sample was analyzed.

TABLE 3

SHALLOW ZONES EXHIBITING HIGHEST POLLUTANT CONCENTRATIONS,
HAMILTON HARBOUR, 1976

Parameter	Station	Concentration (Surface)	Surface Bottom Ratio
Pb	2	970	–
	262	770	11.7
Cd	270	12	>36.
	262	8.7	8.9
	230*	12.5	–
Hg	262	1.1	18.
	230*	1.1	–
Ni	2	140	1.8
	268	77	2.7
Cr	256	670	3.9
	2	540	1.3
	20	490	49.
	230*	550	–
Zn	2	8400	–
	262	6200	18.
Fe (mg/g)	2	340	1.3
	256	170	4.1
	262	117	5.6

Note: All results in µg/g unless otherwise stated.
     * Bottom organic layer found beneath silt.

TABLE 4

R-Mode Factor Analysis of June 1976

Hamilton Harbour Sediment Samples

Variable	Communality	Factor 1	Factor 2	Factor 3
Pb	.9797	.799	.492	.315
Cd	.8966	.784	.180	.500
Ni	.9239	.184	.872	.360
Cr	.9070	.377	.671	.561
Zn	.9851	.849	.452	.245
TKN	.9313	.321	.322	.851
P	.9342	.482	.200	.814
COD	.8874	.431	.780	.307
Hg	.9060	.797	.301	.424
Fe	.9723	.316	.932	.059

FIGURE 1: 1976 HAMILTON HARBOUR SEDIMENT SAMPLING LOCATIONS.
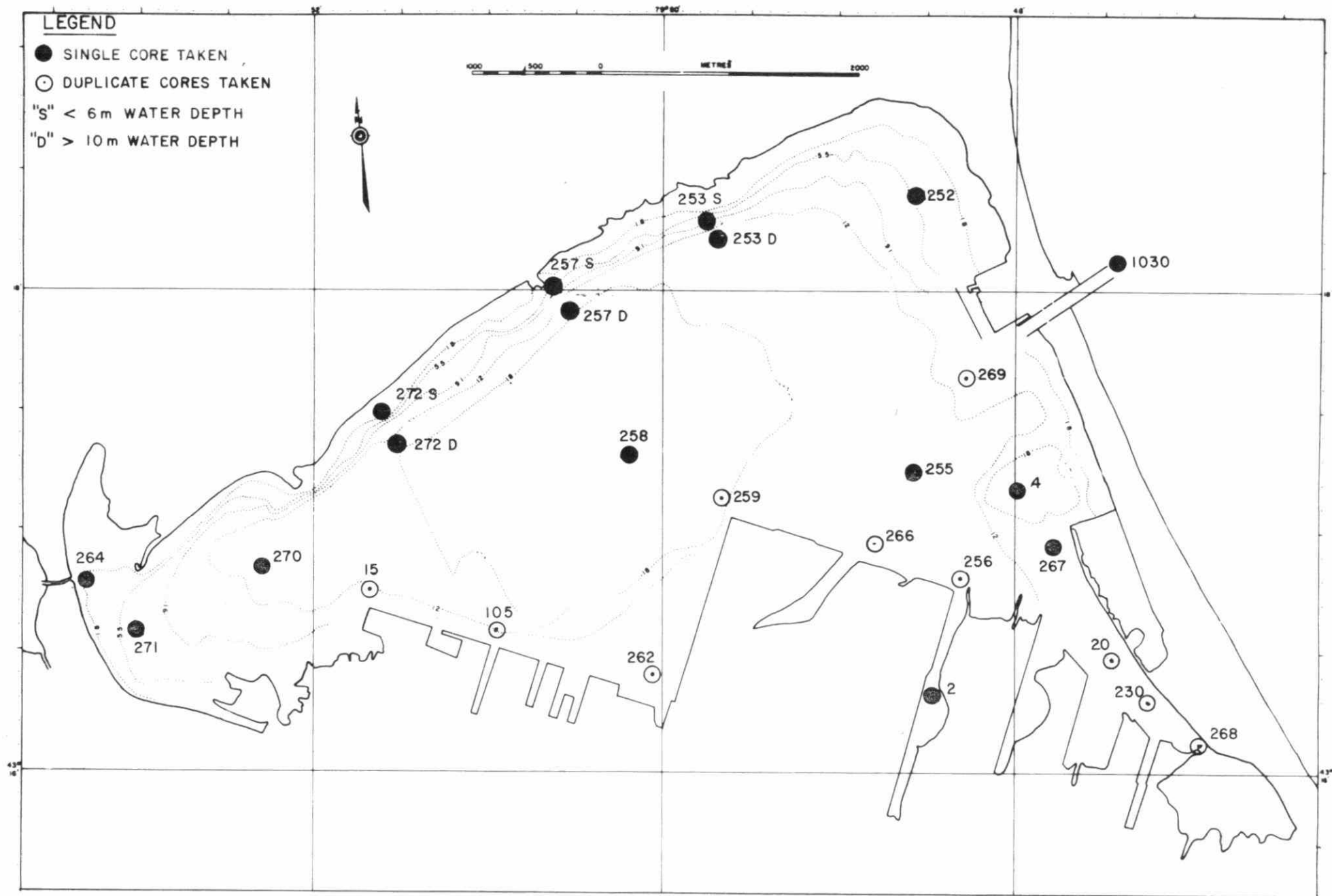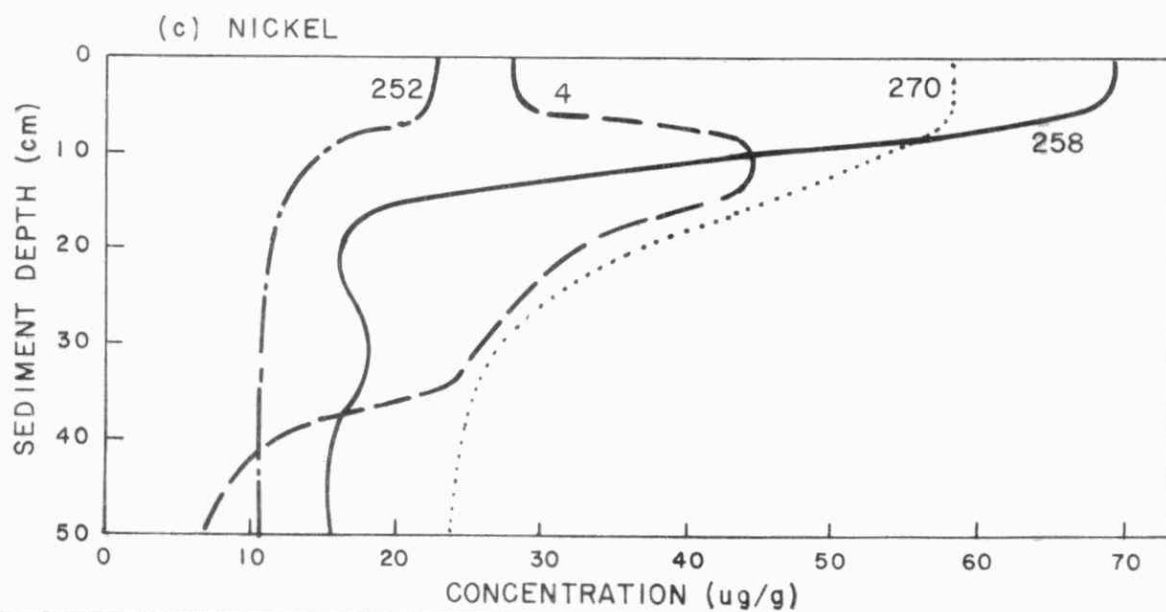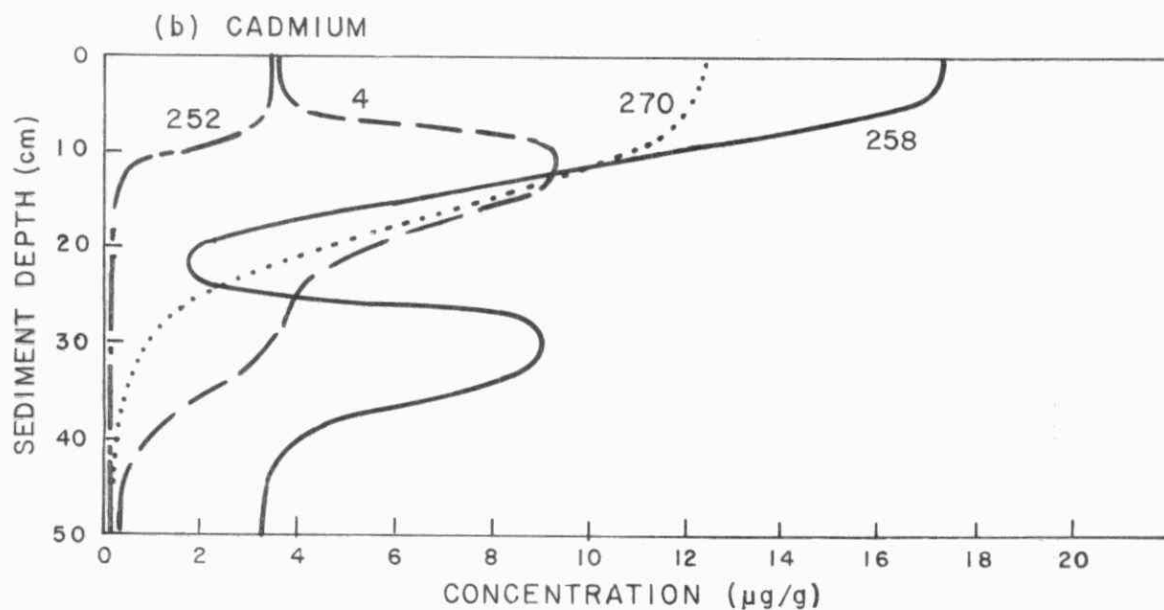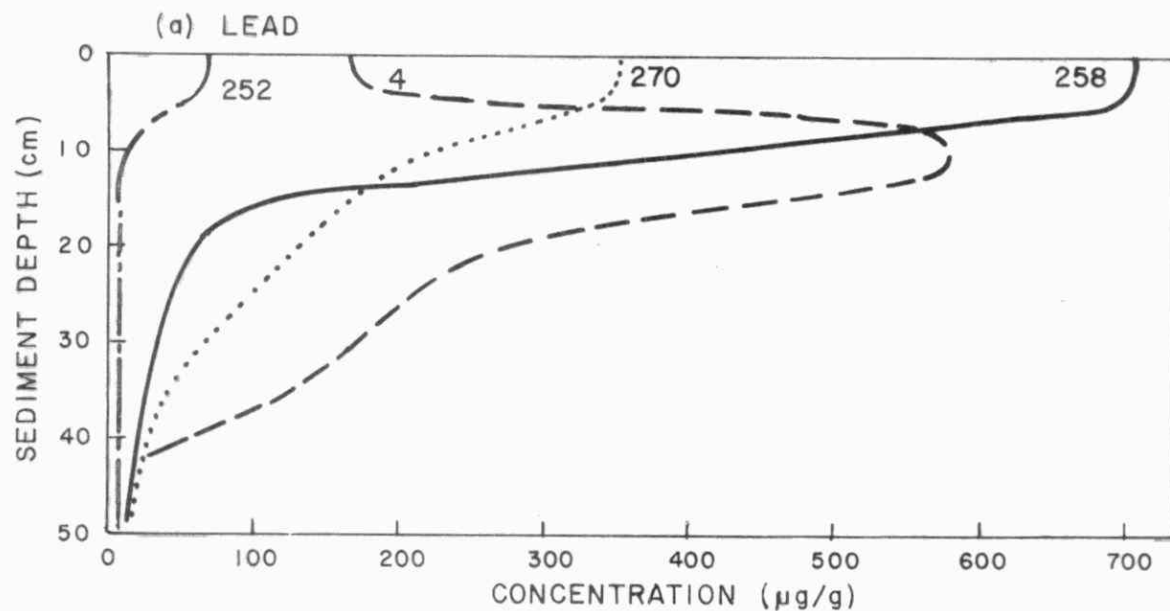
FIGURE 2: VARIATION OF SEDIMENT POLLUTANT CONCENTRATIONS WITH DEPTH, HAMILTON HARBOUR, 1976.
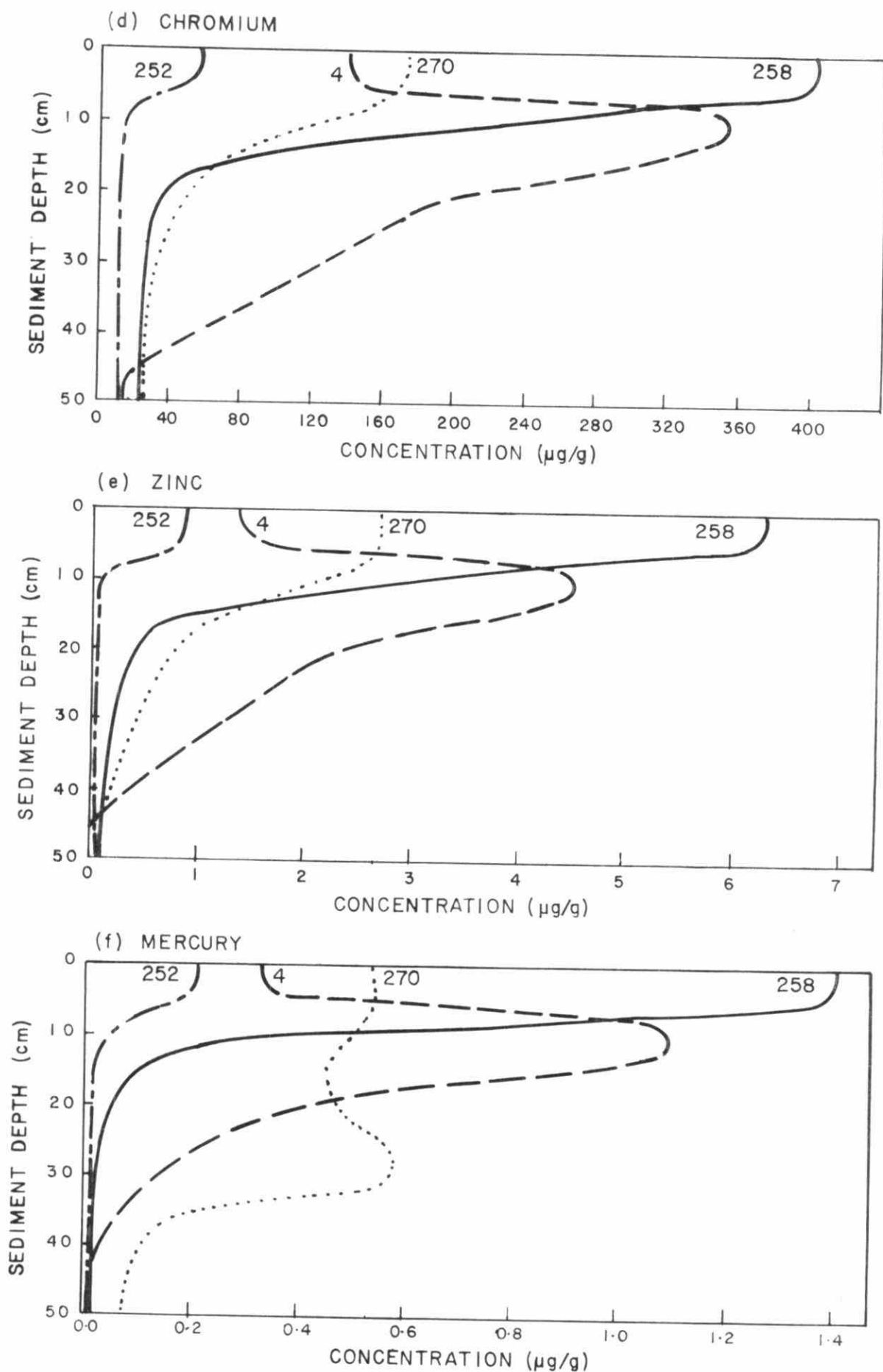
FIGURE 2 Cont,d. : VARIATION OF SEDIMENT POLLUTANT CONCENTRATIONS WITH DEPTH, HAMILTON HARBOUR, 1976.

FIGURE 2 Cont,d : VARIATION OF SEDIMENT POLLUTANT CONCENTRATIONS WITH DEPTH, HAMILTON HARBOUR, 1976.

(j) CHEMICAL OXYGEN DEMAND
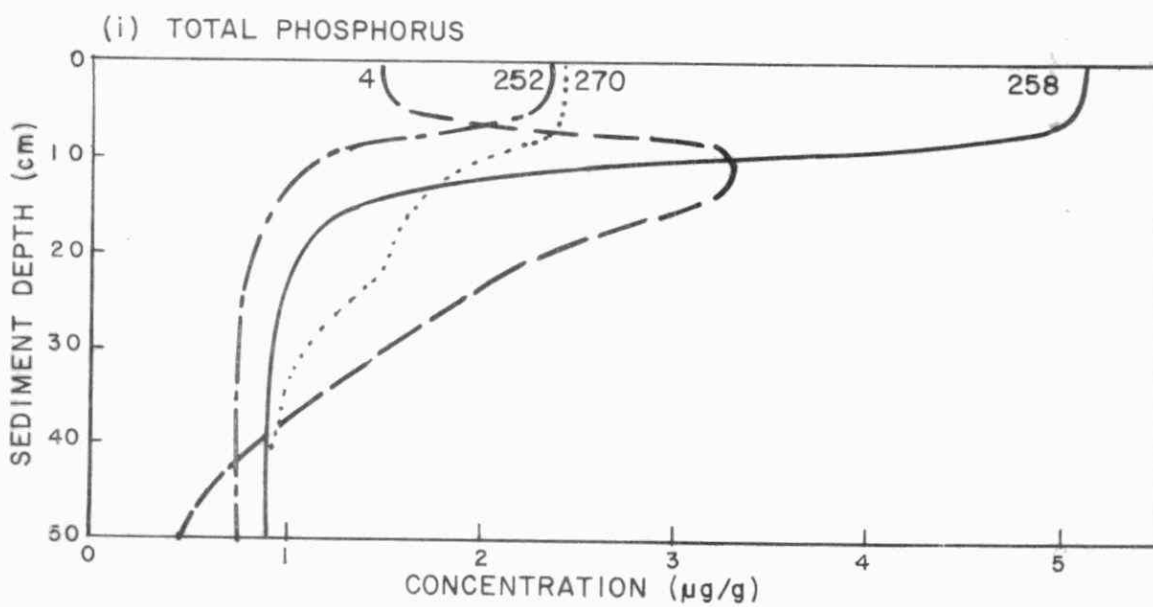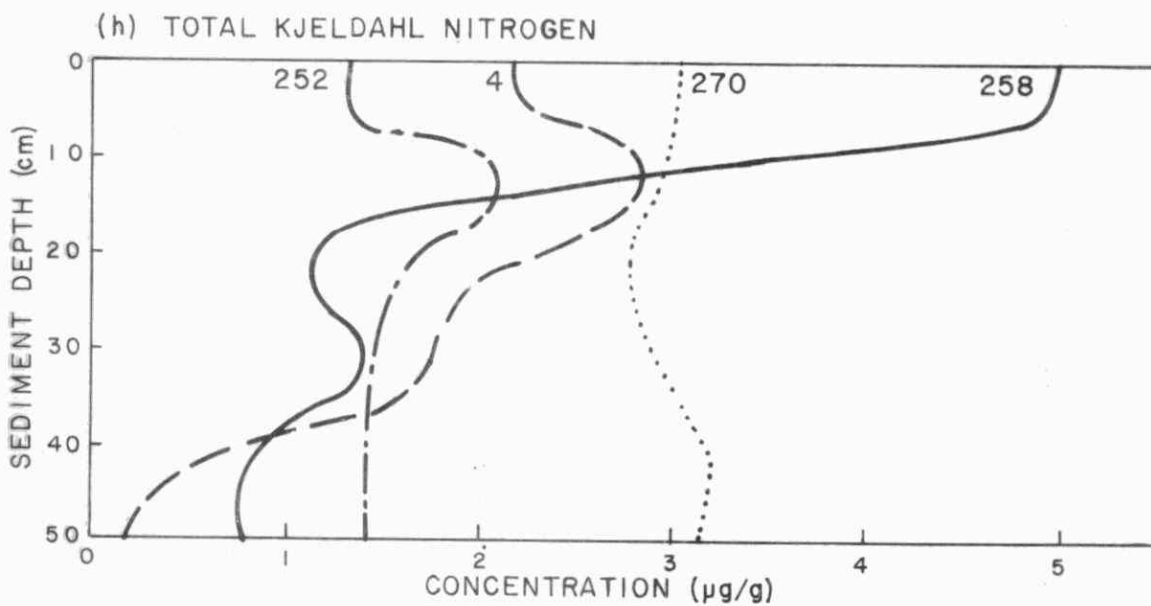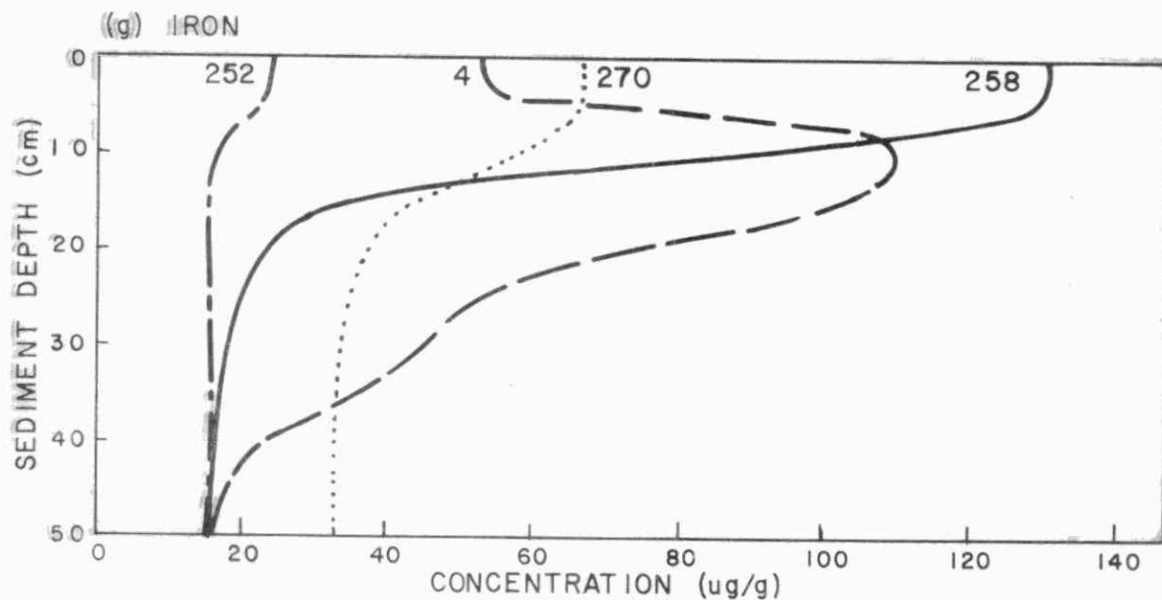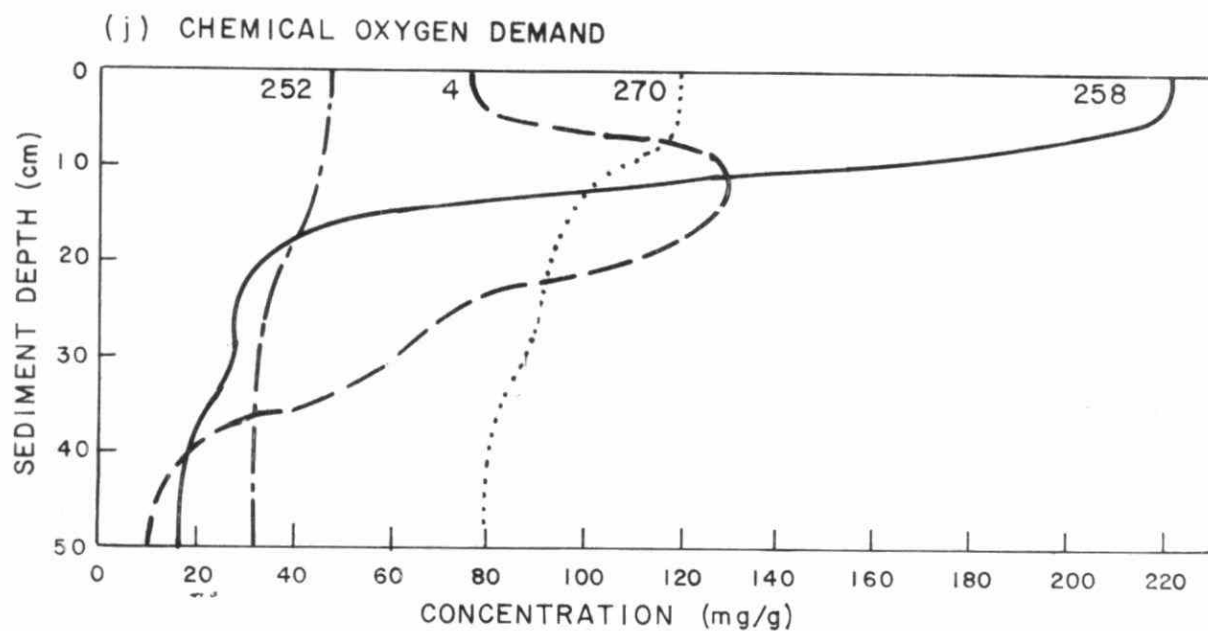
FIGURE 2 Cont,d : VARIATION OF SEDIMENT POLLUTANT CONCENTRATIONS WITH DEPTH, HAMILTON HARBOUR,1976.
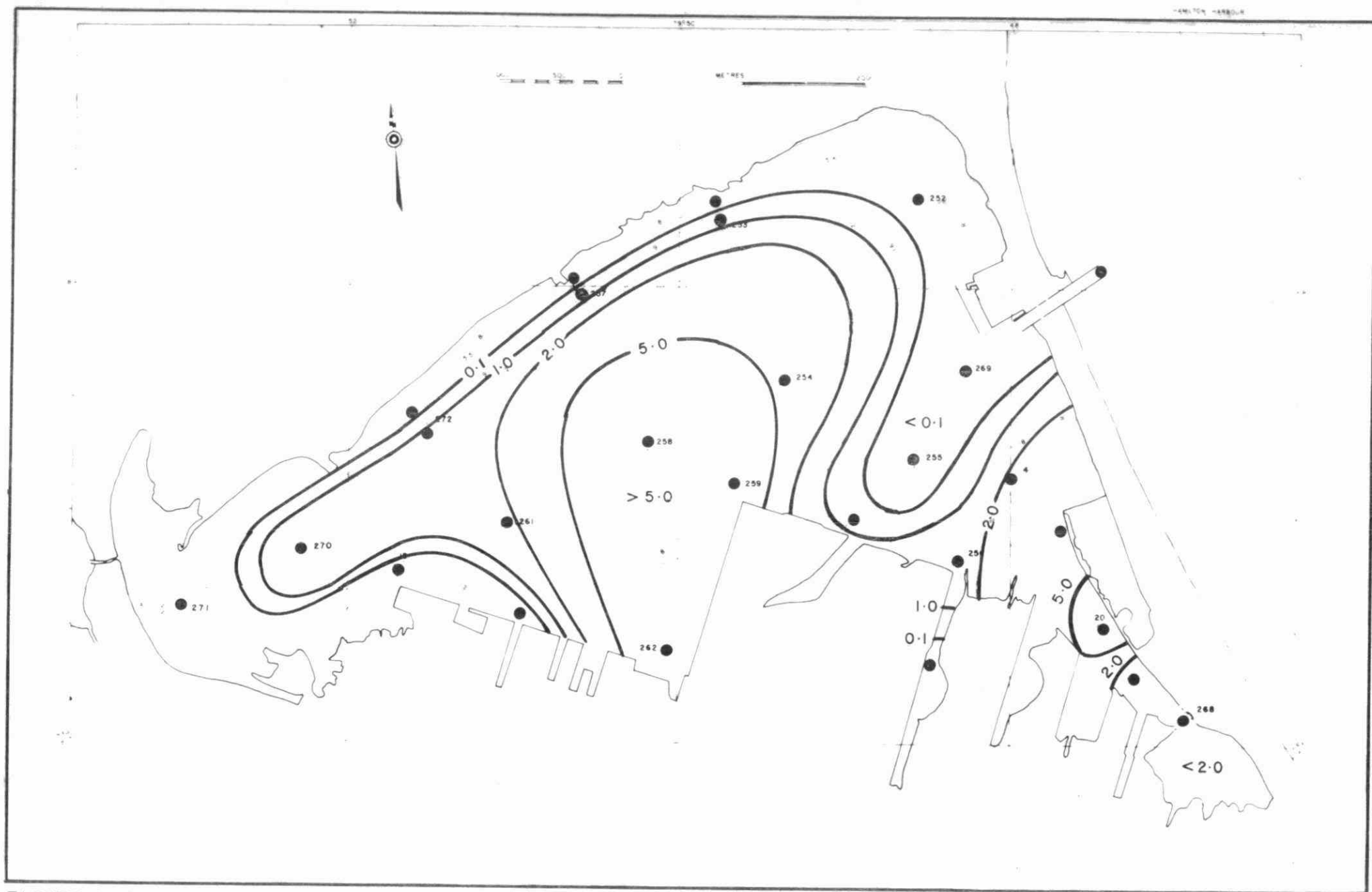
FIGURE 3: SULFIDE CONTENT OF HAMILTON HARBOUR SURFACE SEDIMENTS, µg/g, 1976

FIGURE 4 : ZONES OF "ELEVATED" AND "EXCESSIVE" CONCENTRATION OF ZINC TAKEN FROM 1976 HAMILTON HARBOUR SEDIMENT TOP PORTIONS.

"ELEVATED" REFERS TO CONCENTRATIONS GREATER THAN (MEAN + 2 X STANDARD DEVIATION) OF GREAT LAKES SAMPLES TAKEN FROM RELATIVELY UNCONTAMINATED AREAS (FITCHKO AND HUTCHINSON 1975)

"EXCESSIVE" REFERS TO 5 X "ELEVATED"

FIGURE 5: ZONES OF "ELEVATED" AND "EXCESSIVE" CONCENTRATION OF CADMIUM TAKEN FROM 1976 HAMILTON HARBOUR SEDIMENT TOP POSITIONS.

POSSIBLE LIMIT OF "EXCESSIVE" ZONE, BASED UPON 1975 RESULTS

"ELEVATED" REFERS TO CONCENTRATIONS GREATER THAN (MEAN + 2 X STANDARD DEVIATION) OF GREAT LAKES SAMPLES TAKEN FROM RELATIVELY UNCONTAMINATED AREAS (FITCHKO AND HUTCHINSON 1975)

"EXCESSIVE" REFERS TO 5 X "ELEVATED"

FIGURE 6: ZONES OF "ELEVATED" AND "EXCESSIVE" CONCENTRATION OF LEAD TAKEN FROM 1976 HAMILTON HARBOUR SEDIMENT TOP PORTIONS.

"ELEVATED" REFERS TO CONCENTRATIONS GREATER THAN (MEAN + 2 X STANDARD DEVIATION) OF GREAT LAKES SAMPLES TAKEN FROM RELATIVELY UNCONTAMINATED AREAS (FITCHKO AND HUTCHINSON 1975)

"EXCESSIVE" REFERS TO 5 X "ELEVATED"

D-35
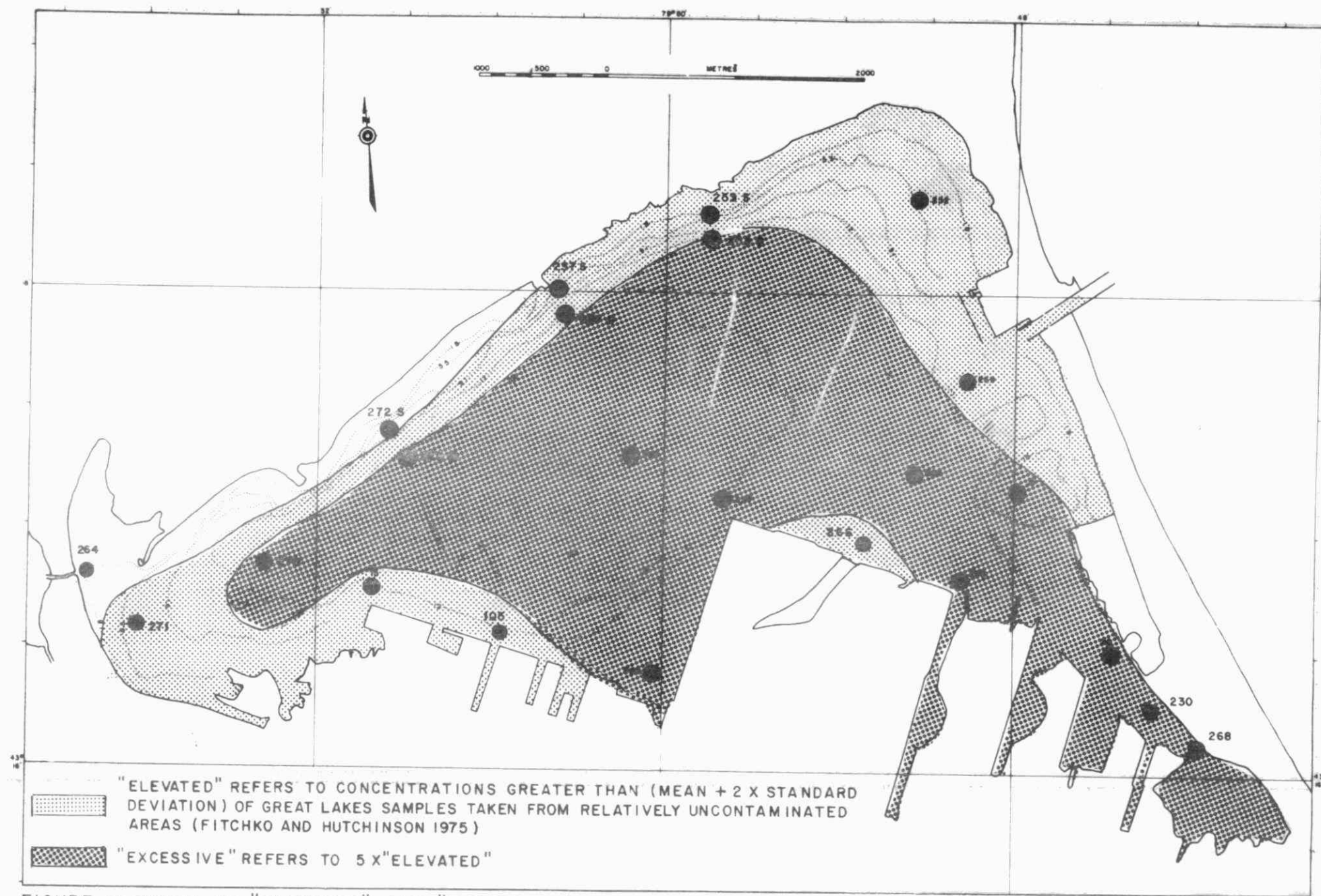
FIGURE 7: ZONES OF "ELEVATED" AND "EXCESSIVE" CONCENTRATION OF CHROMIUM TAKEN FROM 1976 HAMILTON HARBOUR SEDIMENT TOP PORTIONS.

"ELEVATED" REFERS TO CONCENTRATIONS GREATER THAN (MEAN + 2 X STANDARD DEVIATION) OF GREAT LAKES SAMPLES TAKEN FROM RELATIVELY UNCONTAMINATED AREAS (FITCHKO AND HUTCHINSON 1975)

"EXCESSIVE" REFERS TO 5 X "ELEVATED"

"ELEVATED" REFERS TO CONCENTRATIONS GREATER THAN (MEAN + 2 X STANDARD DEVIATION) OF GREAT LAKES SAMPLES TAKEN FROM RELATIVELY UNCONTAMINATED AREAS (FITCHKO AND HUTCHINSON 1975)

NO "EXCESSIVE" PRESENT FOR THIS PARAMETER

FIGURE 8 : ZONES OF "ELEVATED" AND "EXCESSIVE" CONCENTRATION OF NICKEL TAKEN FROM 1976 HAMILTON HARBOUR SEDIMENT TOP PORTIONS.
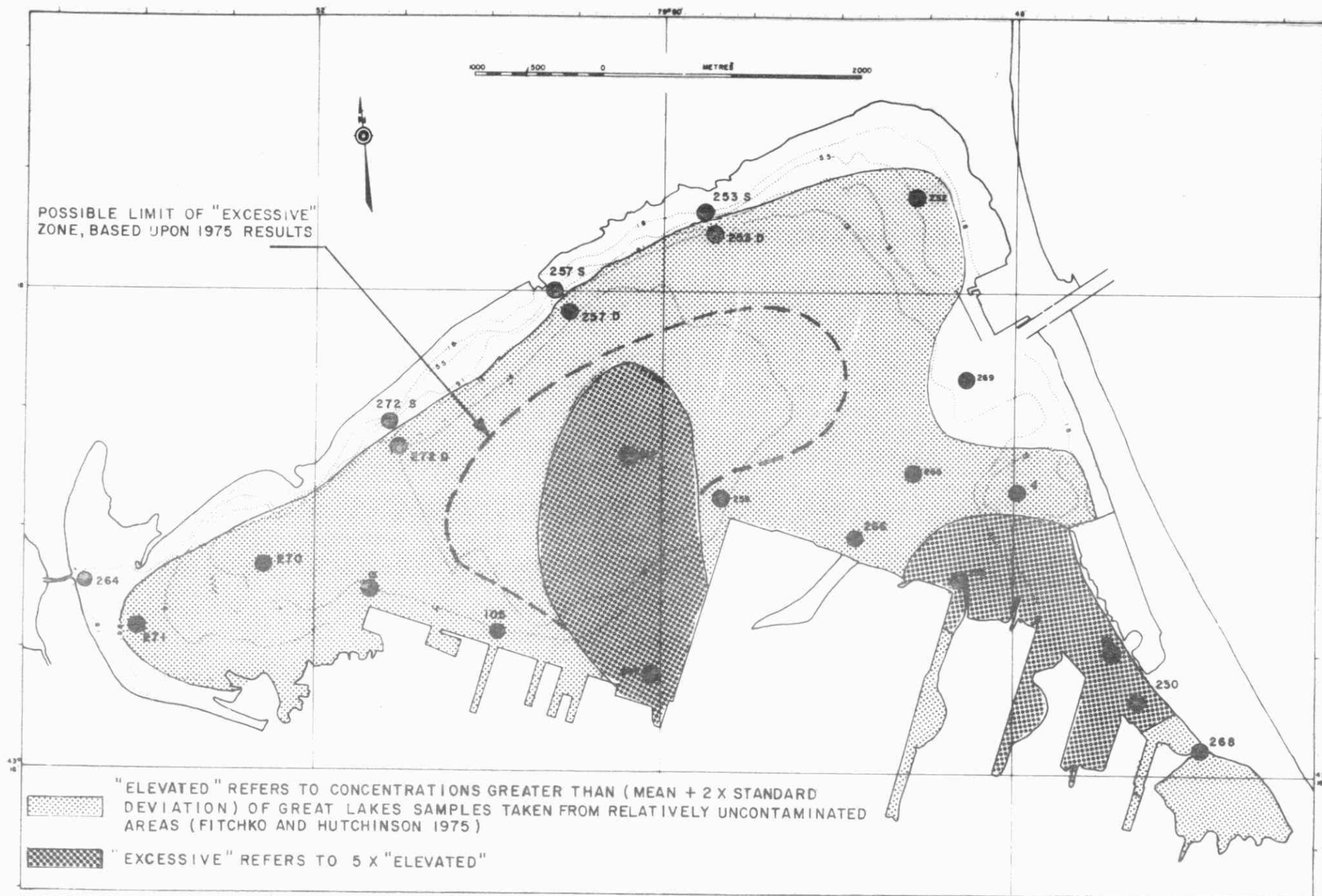
FIGURE 9 : ZONES OF "ELEVATED" AND "EXCESSIVE" CONCENTRATION OF MERCURY TAKEN FROM 1976 HAMILTON HARBOUR SEDIMENT TOP PORTIONS.

POSSIBLE LIMIT OF "EXCESSIVE" ZONE, BASED UPON 1975 RESULTS

"ELEVATED" REFERS TO CONCENTRATIONS GREATER THAN (MEAN + 2 X STANDARD DEVIATION) OF GREAT LAKES SAMPLES TAKEN FROM RELATIVELY UNCONTAMINATED AREAS (FITCHKO AND HUTCHINSON 1975)

"EXCESSIVE" REFERS TO 5 X "ELEVATED"

D-38
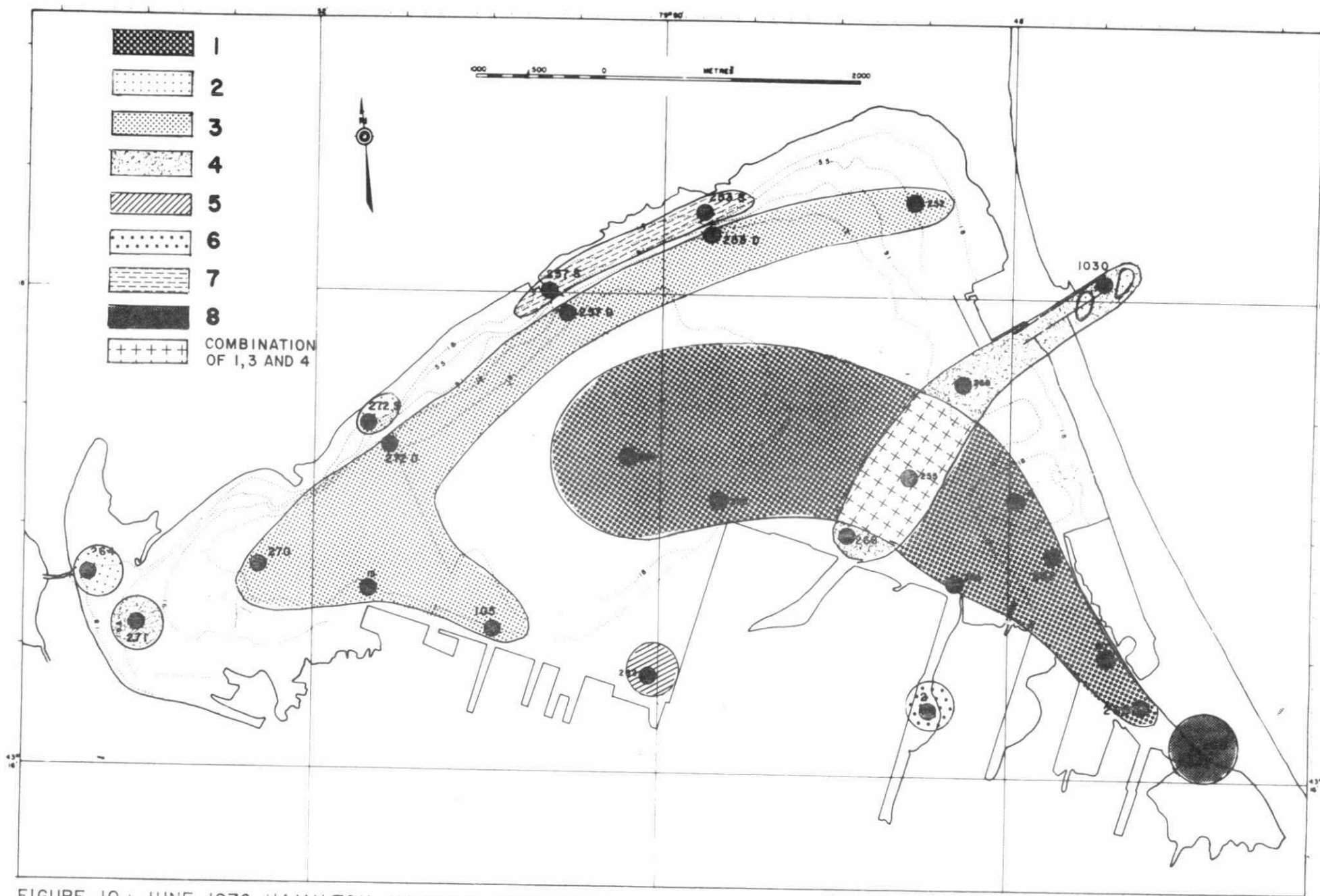
FIGURE 10 : JUNE 1976 HAMILTON HARBOUR SEDIMENTS, 8 FACTORS.

D-39

HAMILTON HARBOUR STUDY 1976

SECTION E

PHYTOPLANKTON AND BACTERIA

SUMMARY

In 1976 phytoplankton were monitored at each metre at station 258. In addition, coincident light and temperature measurements were taken. Major modifications in composition were noted as compared with 1975, although the general associations of population types with thermal regimes were the same. Periods of homogeneous mixing were always dominated by diatoms. These species gave way to a collection of cryptophytes at the end of April when the waters were rapidly warmed and weak stratifications formed. These species are thought to be facultative heterotrophs and can be found to a greater or lesser extent at all times in the harbour.

The rapid attenuation of photosynthetic light in the harbour resulted in a euphotic zone depth of about 4 m. It was this shallow euphotic zone depth combined with a highly variable mixing zone depth which resulted in the rapid shifts in species composition and low productivity in the harbour. The potential production as would be predicted on the basis of nutrient concentrations, was not reached throughout most of the year in the harbour. The maximum assimilative potential was only realized during the early summer when high temperatures coexisted with sufficient oxygen concentrations. This period of longer day length, higher light intensities and a relatively stable mixing depth was dominated by a number of coccoid greens. The rapid flucuations in mixing depths seen in the harbour in 1976 during this period resulted in frequent rapid shifts in the species composition. The physical regime was further reflected in the sustained summer diatom population.

Bacteria samples were collected from April to November at the four major sampling stations. Taxa monitored were selected as being representative of the health aspects of water quality (fecal coliform), the oxidative state of the water column (sulfur oxidizers, sulfur reducers, and Nitrosomonas), and the organic waste assimilation potential of the harbour (heterotrophs).

Population densities showed a general decline for all species monitored except for the sulfur oxidizers which showed large increases in their numbers. These populations are dependent upon the rare event of the coexistence of sulphide and oxygen. Therefore, the increased densities of the sulfur oxidizing bacteria suggests added vertical mixing as a result of the artificial mixing system. All taxa except the sulfur oxidizers showed a general decline in numbers with depth. The sulfur oxidizers however, increased with the depth depending upon the availabilty of reduced sulfur compounds. The sulfur reducers and Nitrosomonas did not show any definite seasonal trends. The heterotrophs were present generally in excess of 10^5 counts per 100 ml and showed a summer maximum. The sulfur oxidizers had densities in excess of 10^6 counts per 100 ml and also showed a summer maximum which declined during isothermal mixing conditions. Both the heterotrophs and the sulfuroxidizers combined to form a major component of the oxygen demand of the harbour. The fecal coliforms again were present in concentrations lower than those prior to 1975 and were generally less than 100 counts per 100ml. Therefore, with regard to health criteria, the harbour would appear to be approaching a state where contact recreation could be permitted. However, a more intensive sampling routine would be required to more fully evaluate this problem.

PHYTOPLANKTON AND BACTERIA

INTRODUCTION

The physical components of coastal areas are complex, and the variability encountered is such that definition of the boundaries which contain the shoreline effects is difficult. Changes in the quality of the water of the shoreline can be classified as natural or man-induced. Natural effects would include runoff, shoreline erosion, sediment transportation and deposition. Man-induced effects are more related to the potential degradation of water quality, but also reflect his dependence on this unique band of water. Although the Great Lakes contain one-fifth of the world's fresh water, a small proportion of that is available as a potable water and waste assimilation resource. Until the interactive nature of the physical-chemical-biological components has been resolved, proper management of this vital zone is indeed tenuous.

Many of the physical processes of Hamilton Harbour are typical of coastal areas. Responses of the harbour to nutrient loadings, waste assimilation and thermal discharges are indicative of the coastal zones properties. Studies on algal production, oxygen utilization and self-purification processes in the harbour environment result in techniques and knowledge which can aid in the proper management of coastal areas of the Great Lakes. These studies result in the ability to improve the harbour environment in the most efficient (ecologically and financially) manner possible, and develop guidelines and bench marks for the other developed sites along the shore of the Great Lakes.

PHYTOPLANKTON COMPOSITION AND PRODUCTION

Laboratory studies of nutrient availability in Lake Ontario (Lee and Cowen 1976; Cowen, Sirisinha and Lee 1977; Sridharan and Lee 1977) have given some insight on the maximum utilization of phosphorus and nitrogen in culture conditions for Lake Ontario waters. Nutrient uptake studies such as those done by Caperon and Meyer (1972) have resulted in more accurate, deterministic models which are used to predict the effects of loadings, or what loadings are required for specific amounts of algal production (Bannister 1974, Lehrman 1974). Such work is immensely valuable for some inland lakes, but the direct application of this work to coastal areas is questionable. Schelske and Stoermer (1972) noted that the ratio of phosphorus to silica in Lake Michigan is 10-20 times that found in natural assemblages of diatoms. They hypothesized that diatoms (which utilize silica as a cell wall component) would become less abundant as silica is depleted, and that the diatoms would be replaced in importance by green algae. Physical processes of coastal areas, however, would continue to favour diatoms with regards to mixing depth and length of time suspended in the photic zone. Nutrient loadings would favour the development of green algae. The actual response of the phytoplankton assemblage is not easily predicted without knowledge of the interactive nature of these parameters, and necessitates the use of data other than simple surveillance records to be able to achieve a realistic resolution.

Investigations in nearshore Lake Ontario have revealed abrupt changes in the chemical and biological components at the thermal bar. Phytoplankton biomass on the inshore was dominated by Stephanodiscus binderanus Kg. (Nalewajko, 1967) as the offshore was dominated by Melosira islandica O Mull. Munawar and Nauwerck (1971) noted that the average biomass of the inshore region was about 25% greater than the offshore zone, and that the inshore population also displayed multiple peaks of abundance over the year. One of the major differences of the inshore and offshore zones was that 65% of the offshore carbon was biologically active, yet only 25% of the inshore was living organic carbon.

Productivity measurements of the inshore areas of Lake Ontario have ranged from 119-2003 mg carbon/m^2/day, as compared with offshore values of 58-1443 mg carbon/m^2/day (Stadelmann et al, 1974). As mentioned by Vollenweider et al (1974) the production mosaics of Lake Ontario do not entirely relate to nutrient loadings from city outfalls (i.e. lower productivity of offshore areas is more a function of mixing depth than nutrient limitation). This is particularly true of Hamilton Harbour where productivity is frequently less than 1000 mg m^2/day despite extremely high nutrient loadings into a confined area.

Productivity in Hamilton Harbour, as in other coastal areas, is depressed by the physical activity of the waters in the inshore zone. Stadelmann et al noted that the thermal profiles of the inshore areas were very erratic with large changes in thermal structure. Similar observations have been described in Hamilton Harbour (MOE, 1977), and are common for the inshore waters of large lakes (Csanady, 1972 a and b; Simons and Jordan, 1972). The coastal waters do not behave as smaller lakes because of the many scales of turbulence, currents and light regimes encountered in them. As noted by Csanady (1972a), the physical processes of this zone combined with their periodicities and dependency on both lake movement and daily climatic conditions produce an environment of extremely high variability. It is to this regime of high physical variability (both small and large-scale variability) that phytoplankton must adapt. In this regard the phytoplankton of Hamilton Harbour can give an insight to the productivity of coastal areas of the entire Great Lakes, and aid in determining the response to development and management of this vital resource.

During 1976, the phytoplankton of Hamilton Harbour were monitored at every meter depth at station 258 to determine their vertical structure (Figure 1). Measurements of thermal structure using a bathythermograph and light penetration measurements accompanied these

collections. Samples were enumerated using the Uttermohl technique with counting procedures of Lund, Kipling and LeCren (1957). Productivity was measured using the light and dark bottle technique in combination with Winkler titration. Chemical data was collected as described in Section C.

There were distinct associations of composition and abundance with the history of the vertical thermal structure of the harbour. During periods of isothermal conditions, diatoms such as Stephanodiscus hantzschii Grun., S. astraea (Ehrenb) Grun., and Asterionella formosa Hass. were abundant. During periods of rapid changes in temperature (either warming or cooling) coccoid greens and cryptophytes tended to dominate. At the maximum summer temperature, abundance increased with a mixture of green algae and diatoms. As compared with 1975 (MOE, 1977), there were major modifications in composition, although the general association of population types with thermal conditions remained true.

Periods of homogeneous mixing were always dominated by diatoms. In the spring, Stephanodiscus hantzchii was by far the most abundant species. Centric diatoms tended to prevail in the more turbid coastal waters, and Stephanodiscus spp. were generally the most common. Other species confined to this period of homogeneous mixing were Asterionella formosa and Diatoma elongatum (Lyngb) Kg. although neither form contributed significantly to the biomass of the harbour (see Figure 2).

After the end of April the harbour waters entered a phase of rapid warming, during which incipient stratifications were formed depending on short-term climatic conditions. At the start of this period, Cryptomonas erosa Ehrenb., C. rostratiformis, and Rhodomonas minuta Skuja were abundant. These species become confined to the upper 2 meters as anoxia became established in the lower waters (see Figure 1). As these species are indicative of organic effluents, it is probable they were utilizing the dissolved organics of the harbour.

A lack of oxygen would prevent heterotrophic assimilation of the available carbon and severely limit the productivity of these organisms. It is this period during which higher temperatures and oxygen co-exist that the assimilation potential of the harbour is at a maximum. As witnessed by the rapid decrease in dissolved oxygen (see Section A) and oxidation of ammonia, the biological communities of the harbour can play a major role in waste assimilation and stabilization should the harbour environment be modified to favour their activity.

During this critical period of rapid warming, coccoid green algae were abundant with rapid shifts in composition being frequently noted. Genera such as Gleocystis, Sphaerocystis, Tetrastrum and Micractinium all represented major portions of the total biomass with no one form gaining dominance over the others for extended periods of time.

When the water column had warmed sufficiently, a more established thermal gradient was developed. There was not, however, a continuous period when a classical thermocline ($1^{\circ}C$ change/meter depth) was evident in the harbour waters (see Figure 3). Very much like profiles reported by Stadelmann et al (1974), the temperature gradients of the harbour were diffused and suggested that erratic changes in mixing depth were a common phenomena in coastal areas. Major upwellings as noted by Stadelmann et al (1974) are not evident in the harbour waters, but may have occurred on a more restricted basis.

Summer species frequenting stabilized lakes are confined to the euphotic zone until in late summer when the water mass begins to cool and the mixing depth greatly exceeds the euphotic depth. These summer species are adapted to high light conditions and as noted by Harris (1973), tended not be adversely affected by photoinhibition. Coastal areas, however, do not have a steady-state condition to which the algae can adapt. There is a critical time period for the

population to adjust to the physical modifications of the
environment. Major modifications such as change in chlorophyll
levels per cell or even change in species require relatively long
periods of time. As the scale of physical processes of coastal areas
form a large continuum of variability, both short and long-term
adaptations are required. Because of this, the phytoplankton
populations of these environments are constantly being modified in an
attempt to maintain maximum productivity.

Summer populations of Hamilton Harbour in 1976 reflected the wide
range of physical perturbations inflicted on them. Many species,
including diatoms, appear in low numbers and as noted by Matheson
(1965) the total standing crop was much less than what would be
expected in a nutrient-rich environment. The large volume of cells
of diatoms common in the summer is evidence of the highly turbulent
motion in this zone. The small Cyclotella meneghinina, Fragilaria
crotonensis (Figure 4) and F. capucina formed moderate size
populations when in most bodies of water they would have settled out
of the water column. Even the large Stephanodiscus astraea was
maintained in suspension throughout the summer period.

Towards the end of the summer many of the larger green algae became
common. Coelastrum, Staurastrum and Closterium were indicative of
the types of species which increased in abundance (Figure 5). This
transition in structure occured very rapidly, and as natural
turbulence increased towards autumn, diatoms became more abundant.
By the end of September, Stephanodiscus astraea was dominant, and a
moderate population was sustained until November (Figure 5). After
this time and during ice cover there was a major decrease in
population to less than 10^6 um^3/ml which was comprised of many
small flagellates and a few diatoms. (Figure 5).

Excluding the periods of isothermal conditions, the phytoplankton of
the harbour were stressed by the physical variability of the zone.

This is somewhat witnessed by the low production of the harbour, and the loss of cells sinking into the hypolimnion. During 1975 and 1976 the most peculiar fact about the phytoplankton was their low productivity rate of less than 1 g C/m^2/day. (Harris, 1976 and Piccinin 1977). This low productivity was not witnessed in light and dark bottle techniques, which suggested oxygen production in a range of 170-2,540 mgO_2/m^2/hr. Photosynthetic quotients (M O_2/M CO_2 tend to be greater than unity depending on light intensity, shifts in metabolism to carbohydrate synthesis or nitrogen sources. In Hamilton Harbour the photosynthetic quotients are very high (averaging 1.5 during the summer of 1976) yet net oxygen production is low (approximately 100 mg O_2/m^2/hr) as noted by the lack of oxygen saturation in the epilimnion.

As the productivity of the eutrophic water of Hamilton Harbour can be a benchmark of responses of production to nutrient loadings in coastal areas general, it is desirable to understand the processes which determine the production rate. Most studies on the productivity of coastal areas have been basically descriptive comparisons, an exception being the work of Harris (1973) who critically analyzed the adapted responses of phytoplankton to the photosynthetic available radiation.

According to Harris (1973) the diatom populations of spring and autumn (periods of homogeneous mixing) are sensitive to exposure to high light. This sensitivity was illustrated by a hysteresis effect (decrease in photosynthetic rates with declining light intensity) which can be assumed to be indicative of how well adapted algae are to light intensity. Harris (1973) noted that green algae tended to be well adapted to summer light regimes in the inshore areas. It is questionable how much of this reflects the degree and period of stable thermal structure (see temperature data of Stadlemann et al 1974) found at the same time. The forementioned authors noted that photosynthetically profiles in coastal zones differed from the classical

type because of non-homogeneous distribution of phytoplankton in the euphotic zone. It would be beneficial if further studies on the hysteresis effect would consider the immediate history of the mixing regime from which samples were obtained. This would be particularly true in Hamilton Harbour as the intensive study distribution with depth would suggest distinct heterogeneity in population abundance and distribution with depth. Phytoplankton populations were being continuously modified by the physical variabilities. No one measurement of production could be taken to be indicative, and it is likely that the overall productivity of coastal areas is lower than would be predicted by empirical models. Phytoplankton apparently do not have the ability to become adapted fully to short-term periodicities which continually modify the mixing structure and light regimes in which they are suspended. Periodicities as short as two hours have been noted in Lake Ontario, and in Hamilton Harbour high frequency variation periods of 0.1 to 0.2 hours are often observed (MOE, 1974). Such processes can directly effect standing crop by removing cells out of the euphotic zone, and indirectly effect production by affecting ability to adapt to the available light regime.

Vertical mixing processes appear to be very effective in Hamilton Harbour with observations on healthy cells mixed deep into the aphotic zone. The harbour waters are characterized by high vertical attenuation of photosynthetic light, resulting in an euphotic depth (of 1% surface light intensity) of about 4 meters. Large spectral modifications might well influence the adapted state of the phytoplankton as blue light (420-480 nanometres) is rapidly attenuated with an average attenuation coefficient ($\mathbf{C}$) of 2.5 where:

$$= \frac{\ln Io - \ln Iz}{Z}$$

and Io is surface light intensity and Iz is intensity at depth Z.

The determinations of actual mixing depth is difficult, but can be estimated as the depth at which the greatest thermal discontinuity occurs. This layer usually acts as pycnocline where there is a suppression of turbulent mixing (Lund et al, 1963). The harbour can have more than one layer of high thermal discontinuity as illustrated in Figure 3, particularly on August 20, 1976 when three distinct thermal layers are recognisable. Although unstable thermal barriers can be formed on warm windless days, these only temporarily alter the vertical structure and mixing rates of phytoplankton (see data regarding July 20). The long-term mixing structure would probably be contained in the lens of water above the layer of maximum thermal discontinuity.

Algal population structure was associated with the thermal profiles of the water column with the standing crop being restricted above the depth of the maximum temperature gradient. On the occasions when more than one distinct thermal gradient occur it is probable that a portion of the standing crop becomes confined to a mixing band which might or might not be included within the photic zone. This would limit the photosynthetic carbon gains of some species, and result in major modifications of composition and abundance as some species adapt and others become moribund. Such layering would have to exist for a critical period of time (3-4 days?) before having a significant effect on the phytoplankton population.

It is tempting to postulate that some species are actually dependent on this layering effect by being adapted to low light conditions or having the ability to survive long periods of aphotic conditions. Only under conditions which favour the development of multiple thermal gradients would such species become dominant forms in the overall phytoplankton assemblage.

This type of vertical structuring is not dependent on the absolute depth scale, but is dependent on the conditions of the mixing regimes contained within the multi-layered systems. Many species encountered in Hamilton Harbour apparently fluctuate with changes in the temperature profile. A predominance at a certain depth does suggest

the ability to adapt to the spatial and temporal stability of
conditions at that depth. "Critical time response" becomes a very
important aspect of the ecology of phytoplankton in coastal areas.

In coastal waters, it is the smaller scale periodicities and
perturbations which prevent the algae from being able to realize
their growth potential particularly in areas of high nutrient
loading. The open lake conditions of greater stability have
depressed nutrient levels and an increased mixing depth. This would
favour cells with low respiration rates and ability to survive in
cooler temperatures. Productivity would be comparable with the
inshore zone but for entirely different reasons. It should be noted
that neither system would favour the production of blue-green algae
which generally prefer warm waters of high stability. Further work
is required to determine if nutrient loadings would result in greater
productivity or if the physical properties of the large lakes are
already a limiting criteria preventing nutrient utilization. It
would seem that chlorophyll $\underline{a}$ concentrations of Lake Ontario of 10
mg/l would already represent the theoretical maximum standing crop in
the euphotic zone of 200 mg Chlorophyll $\underline{a}/m^2$. Nutrient effluents
can possibly be less harmful than thermal discharges which would
result in higher productivity, particularly in the coastal area as
this would tend to favour physical stabilization of the water mass,
and increase the assimilation potential.

BACTERIA

Bacteria samples were collected from April to November 1976 at the
four major sampling stations (#4, 258, 252 and 270). Taxa monitored
were selected as being representative of the health aspects of water
quality (fecal coliforms), the oxidated state of the water column
(sulphur oxidizers, reducers and Nitrosomonas), and the organic waste
assimilation potential of the harbour (heterotrophs). Remaining
groups such as total coliforms (Pseudomonas and Enterococci) which
were sampled in 1975 failed to reveal any useful information and were
considered redundant in the 1976 survey.

In both years (1975 and 1976) fecal coliform populations tended to
decrease with depth (excluding station 4). This would imply that one
of the direct effects of artificial mixing would be the dilution of
the surface concentrations of pathogenic organisms. Other bacterial
groups such as the heterotrophs tended to have high surface
populations utilizing the available oxygen in the well-aerated upper
layers of the water column. Thus, there are no general trends, and
each taxa responds to unique environmental conditions (see Table 1).

In comparison with 1975, the most significant change was the large
population of sulphur oxidizers (Thioparus). These populations are
dependent on the unusually rare event of oxygen and sulphide existing
simultaneously. As large populations are found in Station 258, there
is obviously a significant vertical transfer of oxygen at that
station. Large surface populations of these bacteria at station 4
would reflect discharges of sulphides or reduced sulphur compounds
from within the Windermere Basin, which are carried along the surface
with the warm effluent waters.

Thus, both heterotrophs and sulphur oxidizers combine to form a major
component of the oxygen demands of the harbour. The larger
populations in 1976 would reflect that water column oxygen

consumption was higher that year. Environmental conditions which might have favoured the development of the populations of sulphur oxidizers include reduced vertical stability and the turbulent transfer of oxygen. These conditions which create the situation of oxygen being present in an environment where reduced sulphur substrates are available would be dependent on climatic conditions. It is apparent that artificial mixing would also favour such conditions thereby increasing the stabilization potential of the harbour with regard to reduced sulphur compounds. Because of this interactive and interdependent association of the bacteria and their environment, population responses have been variable at the different stations sampled.

Station 252 is generally well mixed with little evidence of severe oxygen depletion. Fecal coliform levels were high in the early spring probably because of the spring runoff. It is interesting to note that populations at the 6 m depth were higher than the surface concentrations which were frequently acceptable for contact recreation.

Sulphur reducers and Nitrosomonas revealed no definite trends. Heterotroph populations were frequently over 10^5 counts/100 ml and generally declined after reaching a population maximum in May. Decreased summer oxygen levels followed by cooling of the water column might have restricted their development through the rest of the year. Sulphur oxidizers were abundant (greater than 10^6 counts/100 ml) having a summer maximum, and declining during periods of isothermal mixing.

Station 4 had the poorest water quality as fecal coliform counts were frequently over 100 counts/100 ml. Trends over the year were similar at each depth, although there was a tendency for the abundance of heterotrophs, fecal coliforms and sulphur reducers to decrease with depth. The most dominant group at station 4 were the sulphur

oxidizers, particularly near the surface. It is probable these
organisms create a very large oxygen demand along the Windermere
Channel. As high concentrations of reduced sulphur compounds are
required to support such a population, it is interesting to speculate
that sulphide concentrations result in high losses of iron as a
precipitate of FeS. The possibility of phosphorus being controlled
by iron would not seem likely in a situation where reduced sulfur
compounds and organics were sufficient to support these bacterial
concentrations.

Data from station 258 suggested that sulphur oxidizers were limited
by the availability of reduced sulphur compounds at the surface,
unlike those at station 4. Lower in the water column, oxygen supply
was probably limiting as heterotrophs were also decreasing with
depth, and Nitrosomonas populations increased. The sulphur oxidizers
increased with depth depending on the availability of the reduced
sulphur compounds. Fecal coliform counts were low at the three
depths monitored.

Station 270 did not illustrate any distinct trends with depth and was
similar to station 252 except that fecal coliform counts were higher
at the surface than at the bottom. Heterotroph populations decreased
during the year, and sulphur oxidizers peaked in June to early July.
Strong vertical mixing probably masked any depth structuring of the
bacterial populations that did exist at this station.

It is evident that artificial mixing would greatly favour those
bacterial populations (heterotrophs, sulphur oxidizers and
Nitrosomonas which are significant components of the
self-purification processes of Hamilton Harbour. The high
populations at Station 4 indicate that the sulphides and ammonia
loadings to the harbour are rapidly assimilated by the
naturally-occurring bacteria.

With regard to health criteria, the harbour would appear to be
approaching a state where contact recreation could be permitted. A
more intensive sampling routine would be required, however, to assess
the probability of health problems to be incurred from recreational
use of the harbour waters.

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TABLE 1

Bacterial Populations of Hamilton Harbour
1976
(Geometric means over the year)
counts/100 ml

	Surface	Middle	Bottom (20 m)
Station #4			
Fecal Coliforms	98	70	38
Heterotrophs	171,374	42,443	36,917
Sulfur oxidizers	5,838,263	910,582	263,502
Sulfur reducers	227	66	49
Nitrosomonas	735	2,407	2,683
Station #252			
Fecal Coliforms	23	–	73
Heterotrophs	58,749	–	81,779
Sulfur Oxidizers	996,767	–	344,449
Sulfur Reducers	107	–	238
Nitrosomonas	910	–	832
Station #258			
Fecal Coliforms	51	43	13
Heterotrophs	94,546	20,793	21,901
Sulfur Oxidizers	107,015	150,243	223,882
Sulfur Reducers	22	14	20
Nitrosonomas	741	197	1,293
Station #270			
Fecal Coliforms	77	25	36
Heterotrophs	31,690	16,355	23,837
Sulfur Oxidizers	58,889	83,889	128,923
Sulfur Reducers	51	40	38
Nitrosomonas	426	719	577
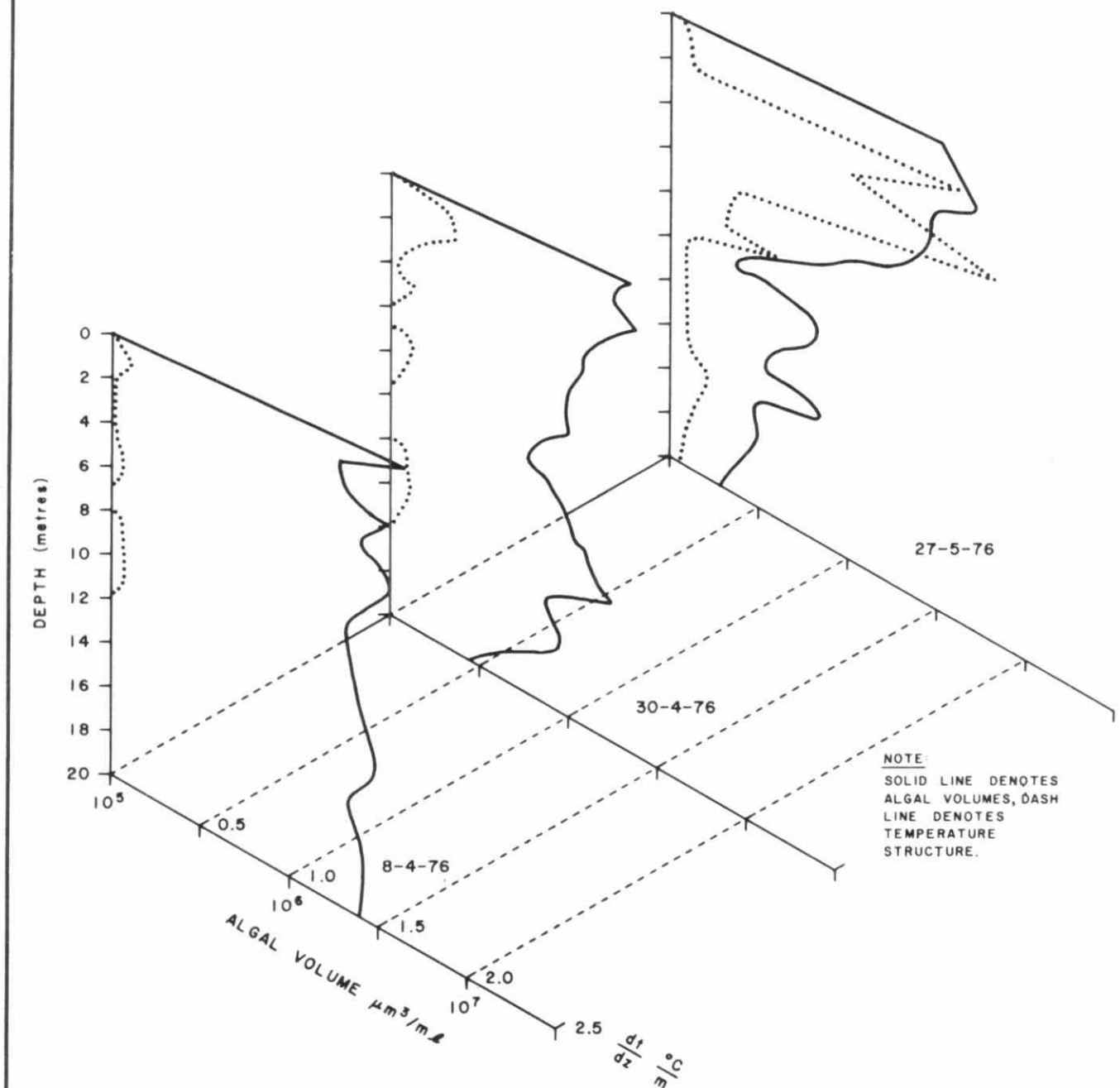
FIGURE 1 — RELATION OF TOTAL ALGAL VOLUME (μm^3 ml^{-1}) AND TEMPERATURE
CHANGE (°C m^{-1}) WITH DEPTH IN THE SPRING OF
1976 AT STATION 258.
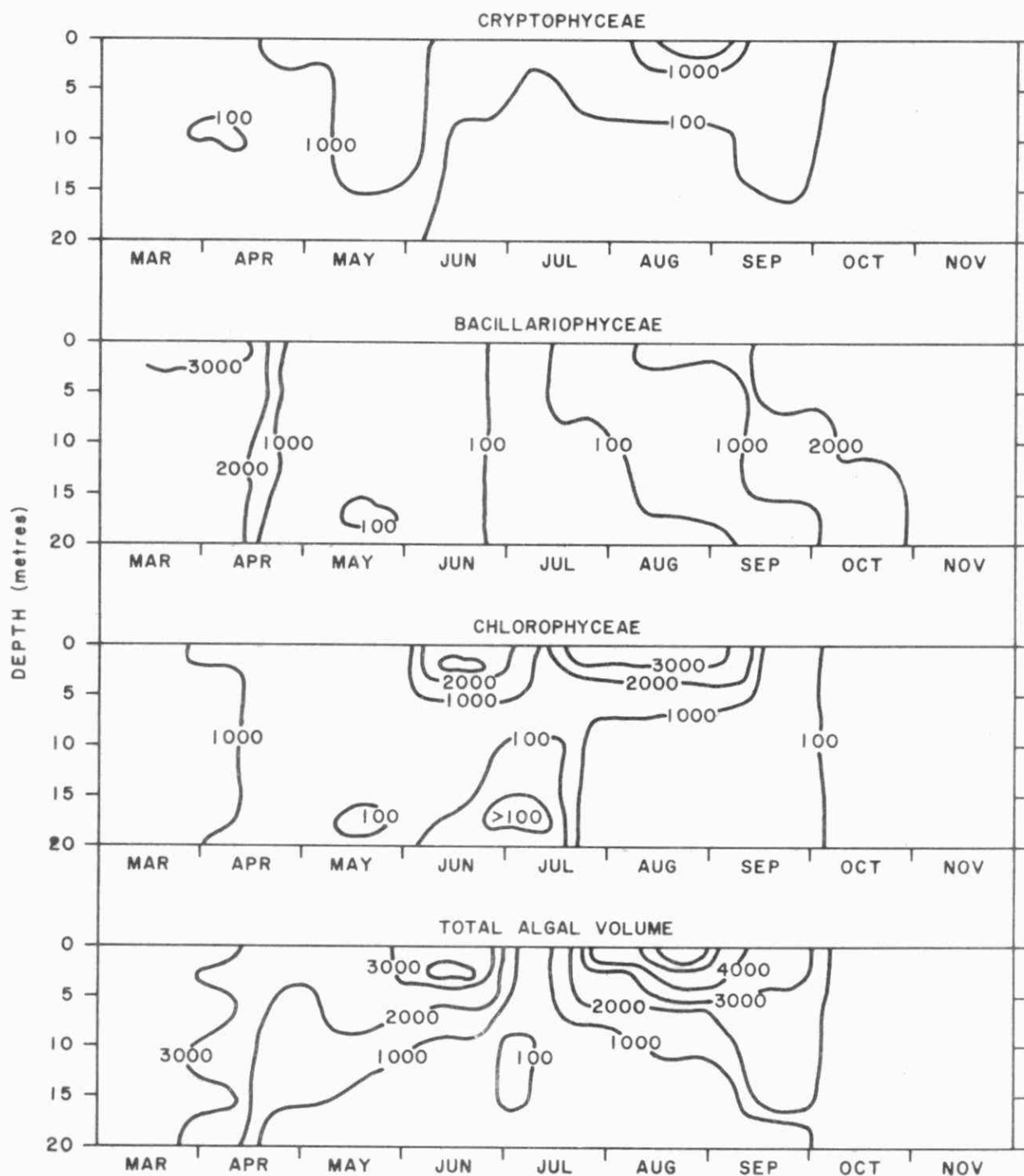
FIGURE 2 — CALCULATED ALGAL VOLUMES X 10³ μm³ ml.⁻¹ AT STATION 258, FOR 1976.
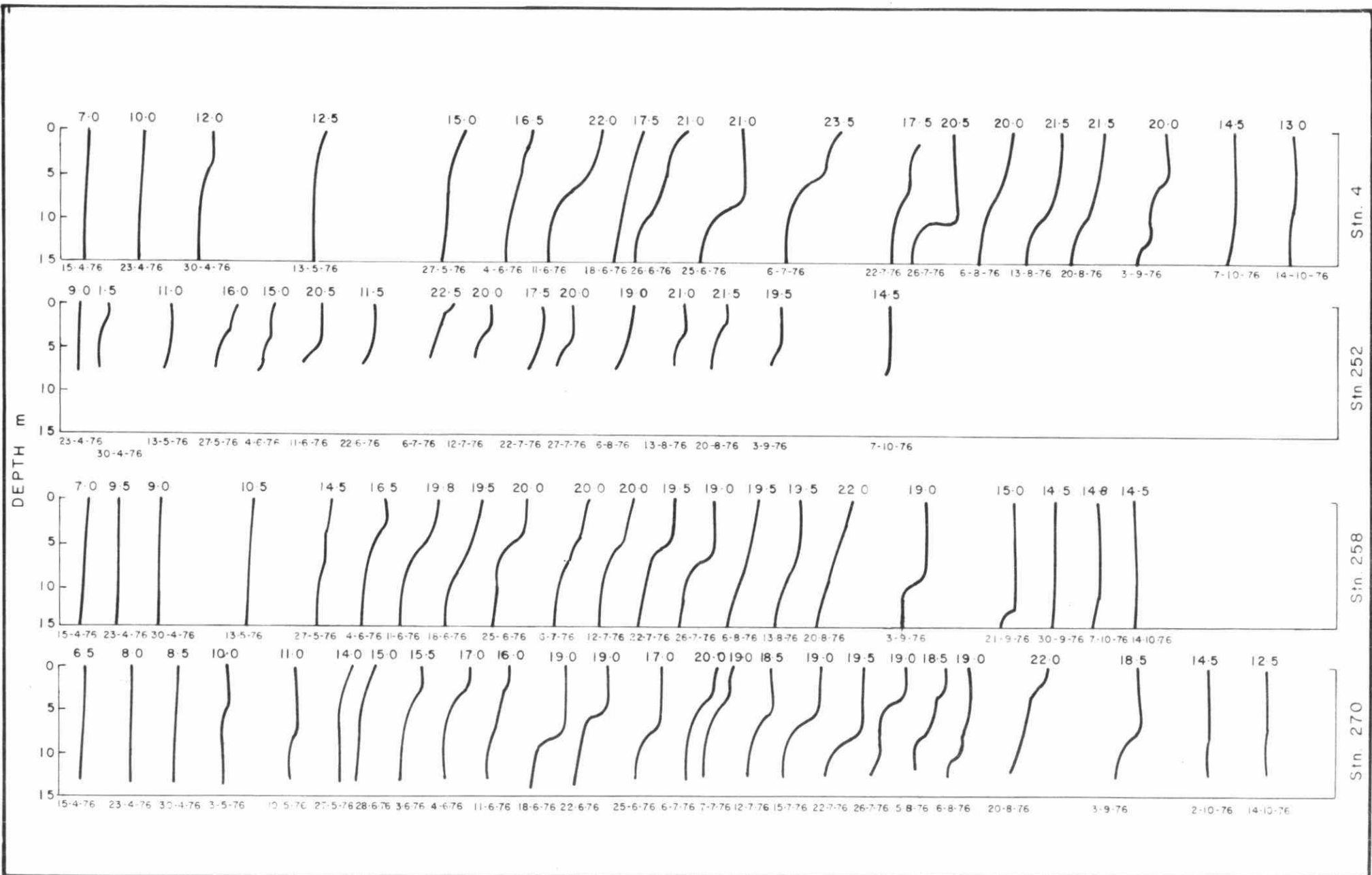
FIGURE 3 : TEMPERATURE (°C) DEPTH PROFILE AT MAJOR SAMPLING STATIONS. HAMILTON HARBOUR 1976
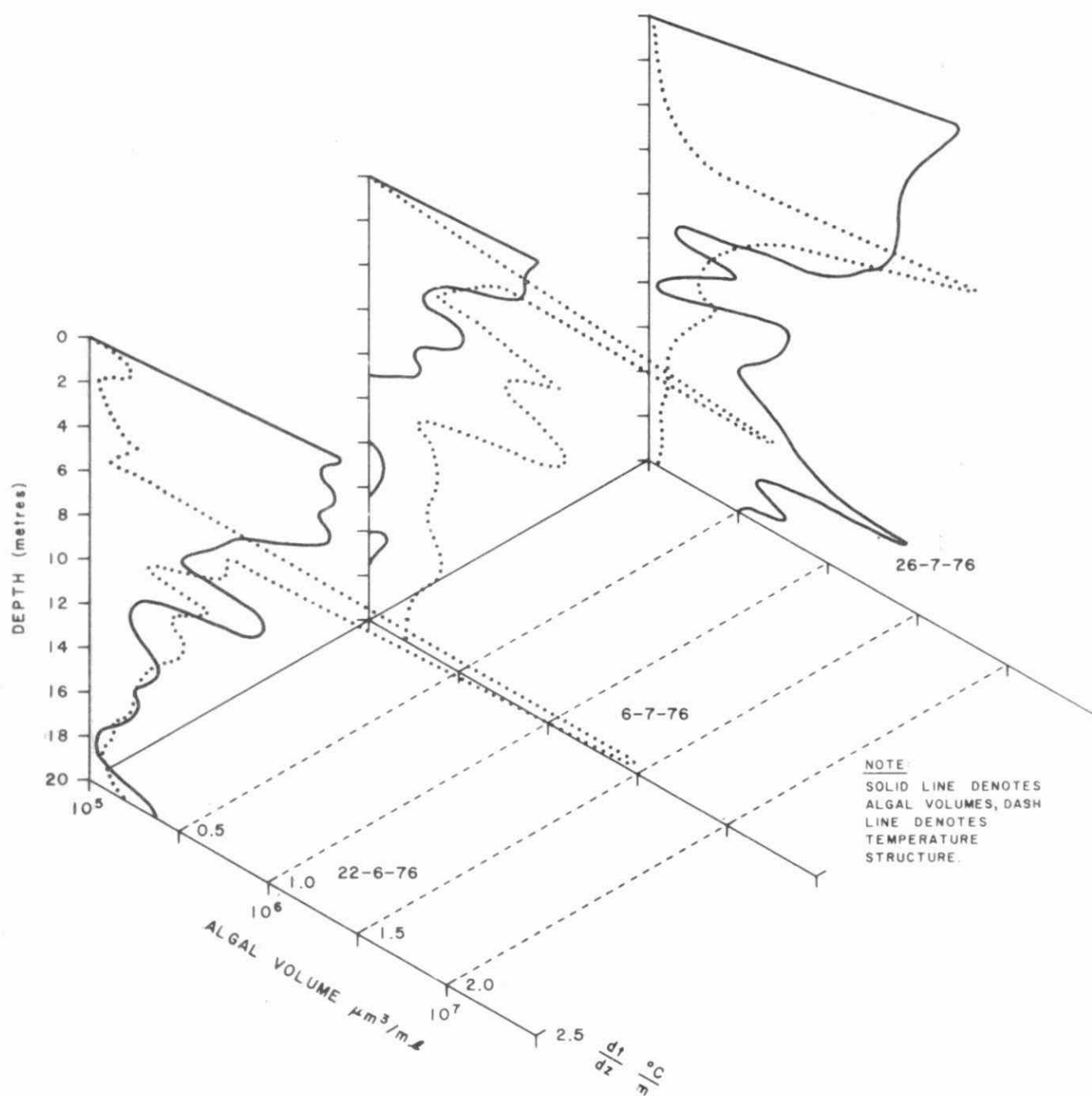
FIGURE 4 — RELATION OF TOTAL ALGAL VOLUME (μm^3 ml^{-1}) AND TEMPERATURE CHANGE (°C m^{-1}) WITH DEPTH IN THE SUMMER OF 1976 AT STATION 258.
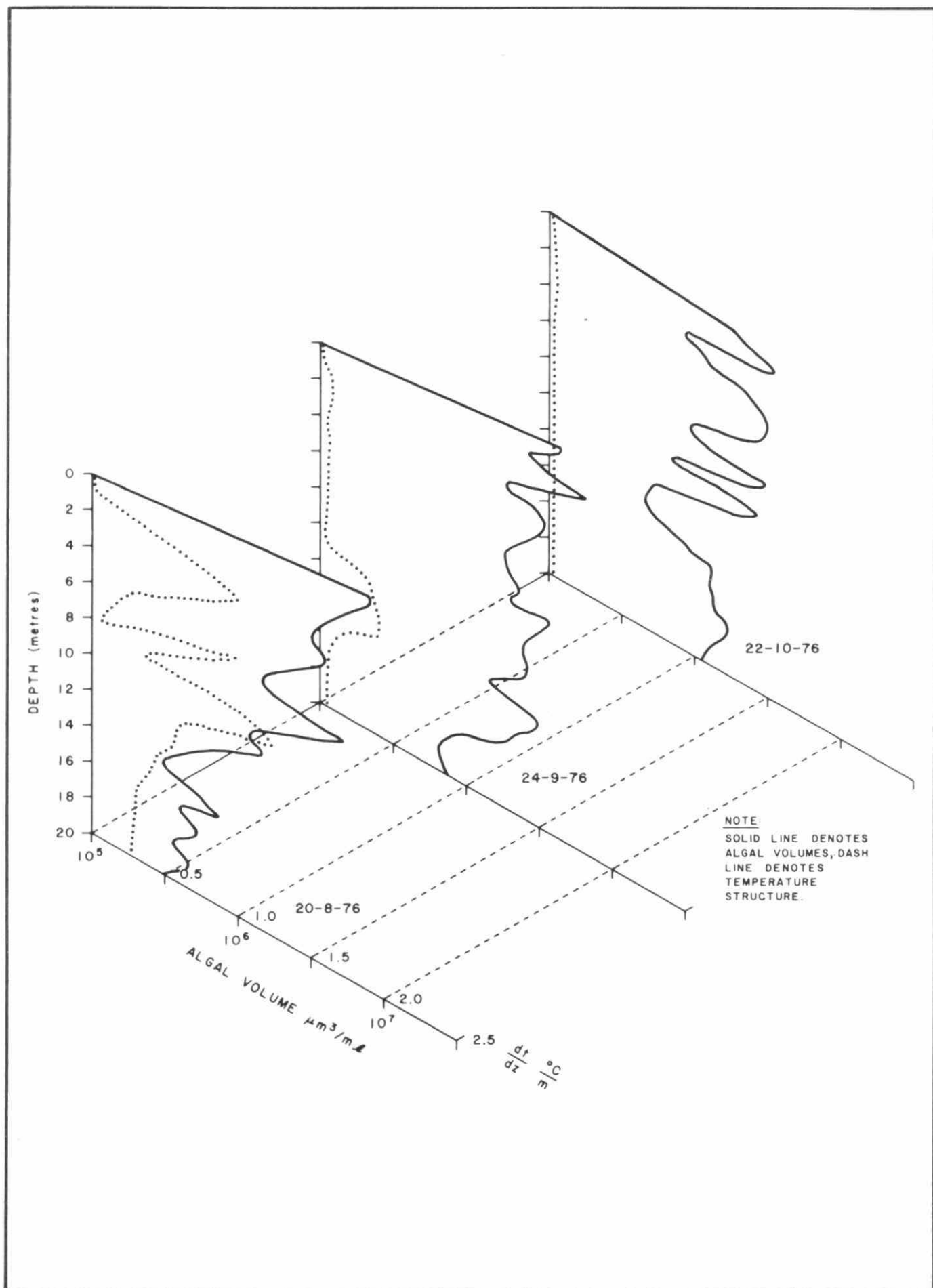
FIGURE 5 - RELATION OF TOTAL ALGAL VOLUME (μm^3 ml^{-1}) AND TEMPERATURE CHANGE (°C m^{-1}) WITH DEPTH IN THE SUMMER OF 1976 AT STATION 258.

HAMILTON HARBOUR STUDY 1976

SECTION F

MASS EXCHANGE

MASS EXCHANGE BETWEEN HAMILTON HARBOUR
AND LAKE ONTARIO

ABSTRACT

The mass exchange between Hamilton Harbour and Lake Ontario waters
through the Burlington Canal, is important for estimating the dissolved
oxygen budget of the harbour. The lake-harbour exchange is caused by
either the unidirectional flow in the canal during isothermal conditions
or the densimetric flow during thermal stratification. During the study
period (September 1975), the canal water was found to be quasi-isothermal;
consequently unidirectional flow existed. Unidirectional flow being the
major source of exchange, a computational method was developed to estimate
the exchange based on excursion distance travelled for each limnological
episode and the final flow in each direction was checked with dissolved
solids budget.

It was estimated that an average of 2.14×10^6 $m^3.d^{-1}$ (25 $m^3.s^{-1}$) of
harbour water flowed into the lake, while 0.77×10^6 $m^3.d^{-1}$ (8 $m^3.s^{-1}$)
of lake water flowed towards the harbour. This accounts for the total
and net daily exchange of 1.04% and 0.50% of harbour volume with net
exchange being towards the lake. The total and net exchanges were
respectively 8 and 4 times the natural drainage. On a monthly average,
more water leaves than enters the harbour, the lake-harbour exchange is
considered important for maintaining and even improving the existing
harbour water quality. The harbour dilution factor was estimated as
0.0019 per day.

MASS EXCHANGE BETWEEN HAMILTON HARBOUR

AND LAKE ONTARIO

INTRODUCTION

Hamilton Harbour is a natural harbour of fresh water at the northwestern
end of Lake Ontario. It is triangular shaped, 8 × 5 km, with a mean
depth of 13 m (see Figure 1) and a water volume of 2.8×10^8 m^3. The
harbour is connected to the lake by the Burlington Canal which is approx-
imately 820 m × 107 m wide × 9.5 m deep. Several creeks drain into the
harbour with mean daily flow of 0.35×10^6 m^3 consequently, the natural
throughput is approximately 0.12 percent of the total harbour volume per
day. The Hamilton and Burlington water pollution control plants dis-
charge a total of 3.2 m^3.s^{-1} of treated effluents. Together with the
natural flow, this results in a total throughput of 0.22 percent of the
harbour volume per day. The major industries located on the south
shores of the harbour use and recirculate 27 m^3.s^{-1} of harbour water
(MOE, 1974).

The harbour is hypertrophic, with mean chlorophyll a 20 µg.ℓ^{-1} and total
phosphorus 40 to 200 µg.ℓ^{-1}. During the summer, the deeper waters of
hypolimnion experience severe oxygen depletion. The lake-harbour
exchange is important in the determination of a dissolved oxygen (DO)
budget for the harbour. Based upon current measurements in the Burlington
Canal, Palmer and Poulton (1976) stated that the net exchange is of the
order of 1% of the harbour volume per day. In the summer, volumetric
exchange of 1% of the harbour volume per day accounts for 19% of the DO
input to the harbour (Polak and Haffner, 1978).

This report is a part of the interdisciplinary water quality study of the
harbour undertaken by the Ontario Ministry of the Environment and McMaster
University for biological (Harris, 1976; Piccinan, 1977), chemical
(Palmer and Poulton 1976; Snodgross, 1976; Chen et al 1977, Polak and
Haffner, 1978) and physical (Palmer and Poulton, 1976) processes.

METHODOLOGY

Freeman et al (1974) found the lake-harbour exchange is partly due to
the Helmholtz mode, and van de Kreeke (1976) has shown that harbours
with restricted entrances such as Hamilton Harbour have faster currents
in the entrance due to the restriction. Helmholtz resonance is a

balance between the kinetic energy of the flow through the canal and the potential energy due to the change in water level within the harbour. The kinetic energy of the flow through the canal causes a unidirectional open channel flow. Dick and Marsalek (1973) attributed the exchange to:

(a) Unidirectional flow in the canal caused by the Helmholtz mode (difference in lake and water levels).

(b) Densimetric flow caused by the thermal stratification; warm harbour water flowing to the lake in the top layer and colder lake water flowing to the harbour in the bottom layer, underneath the warmer water.

The unidirectional flow due to Helmholtz mode, persists while the densimetric flow occurs in the summer season only. The analysis by Dick and Marsalek (1973) showed that the unidirectional flow is the major source of mass exchange through the Burlington Canal.

As the exchange process is complex and variable, only estimates of the exchange volume are possible. Better methods can be formulated for a better data set consisting of current and temperature depth profiles at three cross-sections. In the absence of such data, an episode method is presented using current measurements from a single tower at two different depths.

Currents have been shown to be generally homogeneous across the channel except for the wall boundary layers (about 2 m from the wall). The data may, therefore, be transposed to the middle of the channel. The method outlined below applies to the isothermal case only (as determined by bathycasts and temperature measurements) when the flow is unidirectional at any time.

The calculated Reynolds numbers ranged from 0.7×10^5 to 9.5×10^5 (length scale = hydraulic radius of channel; velocity scale were varied from velocity of mean flow in either direction to the arithmetic mean velocity of the record) and therefore the flow was considered as fully

developed turbulent in Burlington Canal. A universal velocity distribution (Chow 1959; p.201) for the turbulent flow in open channel can be rewritten as:

$$V_1 - V_2 = 2.5 \; U_* \; \ln \; (y_1/y_2) \; \ldots\ldots\ldots\ldots\ldots \; (1)$$

where V_1 and V_2 are velocities at distances y_1 and y_2 respectively from the channel bottom.

U_* is the shear velocity.

Initially let the water travel a mean excursion distance $\overline{X}_1$ towards the harbour with a mean velocity $\overline{U}_1$ for a time episode t_1, resulting in flow q_1. Due to the Helmholtz resonance, the flow reverses its direction to travel a mean excursion distance $\overline{X}_2$ towards the lake with a mean velocity $\overline{U}_2$ for a time episode t_2 resulting in flow q_2.

The excursion distances, lying between 50 and 1100 m, were divided into 50 m classes upto 400 m (about half the channel length) and into 100 m classes for excursions greater than 400 m. The mean of these classes E_i were ranked with E_1 being the maximum ($E_1 = 1050$ m). For each E_i, the flows q_1 and q_2 were grouped and summed, such that:

For $i = 1$ to n

$$H_i \quad = \Sigma \; q_1 \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (2)$$

$$L_i \quad = \Sigma \; q_2 \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (3)$$

$$T_i \quad = H_i + L_i \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (4)$$

where:

H_i is the total flow towards the harbour,

L_i is the total flow towards the lake

T_i is the total exchange through the canal.

The above flows were then accumulated as:

$$Hq_i = \sum_1^i H_i \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (5)$$

$$Lq_i = \sum_1^i L_i \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (6)$$

$$Tq_i = Hq_i + Lq_i \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (7)$$

A critical excursion distance E_c can be evaluated by the dissolved solid (DS) budget as well as the plot of E_i against T_i. It will be shown that the flows, corresponding to excursion distance less than E_c, do not contribute to the mass exchange.

Therefore, for $\quad i = c$ and $\quad E_i = E_c$

$$Q_1 = Hq_i = Hq_c$$
$$Q_2 = Lq_i = Lq_c \quad \dots\dots\dots\dots\dots \quad (8)$$

where Q_1 and Q_2 are total flows towards the harbour and lake respectively.

Equations (5), (6) and (7) yield accumulated or total flows when flows corresponding to excursion distances less than E_i are neglected.

It is apparent that the mass exchange through the canal results in dilution of conservative contaminants (e.g. dissolved solids). Such a dilution factor may be computed as:

$$D = (C_h - (C_{im} + C_\ell))/(0.5 \times (W_1+W_2) \times p) \quad \dots\dots \quad (9)$$

where:

$\quad$ D $\quad$ = Dilution factor per day

$\quad$ C_h $\quad$ = Estimated mass of conservative contaminant transferred from the harbour to the lake by the exchange process during p days.

C_ℓ = Estimated mass of conservative contaminant transferred from the lake to the harbour by the exchange process during p days.

C_{im} = Estimated mass of conservative contaminant added to the harbour by the industrial and municipal discharges during p days.

W_1 = Estimated mass of conservative contaminant present in the harbour, initially.

W_2 = Estimated mass of conservative contaminant present in the harbour after p days.

EXPERIMENTAL OPERATIONS

Two self-recording current instruments were operated at 6.1 m and 7.5 m from bottom on a single tower in Burlington Canal (9.5 m total depth) from 14 August to 13 September, 1975. As the compasses of the Geodyne-type instruments have historically malfunctioned in the Burlington Canal, only Plassey current instruments (Model MO 21) were deployed. Prior to the installation, the instruments were calibrated and checked in the laboratory and set to record current directions, water temperature and current magnitudes (speed integrated over 10 min.) every 10 minutes.

DATA REDUCTION

Water temperature and current speed data were pre-whitened (numerically smoothed) after Blackman and Tukey (1959; p.29, 39, 174) using binomial weights after Panofsky and Brier (1968; p.150) as follows:

$$C_m = N! \, / (m! \, (N-m)!) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (10)$$

where C_m is the binomial coefficient and these converge on the shape of the normal distribution curve as N increases.

For the present data at 10 minute intervals, N = 4 results in the best smoothing. The binomal weights are then computed as:

$$S_m = C_m \bigg/ \sum_0^m C_m \quad\text{.......................................} \quad (11)$$

where S_m are the binomial weights for smoothing the data. The current directions were not smoothed as the water flow was restricted along the canal axis. The data were divided into monthly records for August and September.

Water Temperature

Figure 2 shows two bathythermograph casts in the Burlington Canal on August 15 and September 5, 1975. Thermal stratification on August 15 is extensive while conditions appear to be approaching isothermal on September 5, 1975. During August, thermal stratification existed in the canal creating a thermal lense. During thermal stratification, water movement data at four or more different depths are considered necessary to compute mass exchange as water may be moving in opposite direction at different levels. The available data at two levels (1.4 m apart vertically) were therefore not sufficient to compute mass exchange when stratification existed. The September data during nearly isothermal (unidirectional open-channel flow) conditions were processed for the computation of mass exchange as follows.

The frequencies of occurrence for hourly temperature values were computed at both levels including the mean, standard deviation, maximum and minimum (see Figure 3). The mean temperature at upper and lower levels was 20.5°C and 19.8°C respectively with standard deviations of 1.8°C and 2.3°C. A simple correlation coefficient between the two temperature series was computed to be 0.81 and χ^2 for the two series was estimated to be 11.60 with 11 degrees of freedom. As $\chi^2_{0.95,11} = 19.68 > \chi^2_{11} = 11.60$, it was concluded that temperatures at the two levels were not significantly different providing verification of quasi-isothermal conditions. The computer plotting of currents at both levels (see Fig.4)

indicated that the flows were approximately in phase, consequently the quasi-isothermal conditions prevailed in the Burlington Canal. Cross-correlations of water temperatures between two levels were calculated for up to 30 h lags and are presented in Figure 5.

Water Movements

Two dimensional frequency of occurrence of current magnitude and direction at both levels were computed (See Appendix) and summarized in Table 1. At both levels, the maximum speed recorded was about 45 $cm.s^{-1}$. The arithmetic average speed at upper and lower levels were 12.1 and 11.1 $cm.s^{-1}$ respectively while the resultant speeds were 4.4 and 2.5 $cm.s^{-1}$ respectively. Using the upper level speeds and the universal velocity distribution of equation (1), the arithmetic average and the resultant speeds at lower level should be theoretically 11.7 and 3.9 $cm.s^{-1}$. The actual arithmetic average speed of 11.1 $cm.s^{-1}$ is very close to the theoretical average speed of 11.7 $cm.s^{-1}$. However, the actual resultant speed of 2.5 $cm.s^{-1}$ appears significantly different from the theoretical resultant speed of 3.9 $cm.s^{-1}$. The ápplicability of the universal velocity distribution equation to a channel with time reversing flow is not known. One would expect the velocity to be lower allowing time for the velocity profile to develop after each flow reversal.

Although the currents were in phase at two levels most of the time, there were small periods (4 to 7 percent) of time when currents were out of phase due to some unknown physical processes. The difference between the percentage of time the currents go towards the resultant and in the opposite direction is 19 for the upper level and 8 for the lower level. This may explain the smaller resultant currents at the lower level.

The smoothed current velocities were resolved along and across the canal and then averaged over an hour. The hourly values of speed and tempera-ture were subjected to the spectral analysis (see Table 2) by standard numerical techniques and the Hanning of the coefficients after Blackman and Tukey (1959; p.34, 171). Cross-coherences between currents and

water temperatures between the two levels were computed and significant coherences (95% confidence) are summarized in Table 3.

Exchange Calculations

As the currents going towards the channel wall do not contribute to the flow, all currents falling in the shaded area of Figure 6 were neglected. Water movements in the shaded area ranged from 7 to 10% of the time. These few instances may be due to the instantaneous direction readings recorded by the Plessey instruments. Normally, the water movements in the canal should be parallel to the axis of the channel. The rest of the currents at both levels (90-93%) were then resolved along the channel axis.

The resolved speeds were then computer plotted for both levels (see example in Figure 4). Points to the left of the Zero Speed Line (ZSL) indicate flows towards the harbour while the points to the right of the ZSL show flow towards the lake. The date and time are also printed. When currents are mainly towards the walls, no points are printed during that interval. The points on the printout were then joined manually, the dotted lines indicate interpolation in the absence of one or more data points. Figure 4 shows that the two instruments recorded flows approximately in phase. As expected, the flows shift to and from the harbour each time the time history plot intersects the ZSL (see Figure 4). Between two such convective crossings, the flow persists in one direction. Now, if the average speed during such an interval is computed and a time interval noted, it is possible to calculate the excursion distance ($\overline{X}_1$ or $\overline{X}_2$) a particle may travel during that episode. The volume of such flow (q_1 or q_2) was also calculated (see Appendix). This process was repeated for the complete record of 13 days. Computations according to equations (2) to (7) were carried out and tabulated in Table 4. Thus, total flows toward the harbour and toward the lake were calculated for a period of 13 days for all excursion distances. Flows through the canal for different excursion distances are also presented in Figure 7 showing that small excursions (<325 m) are responsible for a maximum of 16% of the

total exchange through the canal. However, the small excursions cause water to move within the confines of the canal length and never leave the canal. Therefore, these small excursions are responsible for exchange much less than the indicated 16% of the total. Thus, flows associated with small excursions (<325 m) are neglected in the final estimates. A summary of exchange results is presented in Table 5. During the first 13 days of September 1975, the average flow rate of water from the lake to the harbour was 0.8×10^6 $m^3.d^{-1}$ or 9 $m^3.s^{-1}$ while the average flow rate of water from the harbour to the lake was 2.1×10^6 $m^3.d^{-1}$ or 25 $m^3.s^{-1}$. This represented a total exchange rate of 2.9×10^6 $m^3.d^{-1}$ or 34 $m^3.s^{-1}$ (1% of the harbour volume per day). The mass exchange for the harbour is schemetically presented in Figure 8.

Dissolved Solids Budget

The dissolved solids (DS) mass in the harbour were estimated for August 15 and September 16, 1975, utilizing a modified Boyce (1973) method similar to Polak and Haffner (1978) and the DS vertical profile at the harbour stations (see Figure 1 and Appendix). Dissolved solids were computed as $0.65 \times$ conductivity. The harbour was divided into 500×500 m cells each having constant depth. All cells were divided into one metre layers to the bottom. The nearest DS profile to a cell was utilized to compute the DS content of the layer and the cell. The contents of all layers and cells were then summed for the total content of the harbour (W_1 in equation (19)). Similarly, the content of the harbour after 32 days was also estimated (W_2 in equation (19)).

The total DS added to the harbour during the 32 days (August 15 to September 16) were estimated from industrial and municipal discharge data. Similarly, the DS addition (or reduction) to the harbour due to mass exchange was computed. The results of the above computations are presented in Figures 9 and 10 indicating that the mass balance of DS can be approximately achieved if flows corresponding to excursions less than 325 m are neglected.

Knowing the average values of DS in the harbour as well as in the lake (just outside the Burlington Canal on either side) and the estimated

flows in the canal in either direction, it is possible to calculate C_ℓ and C_h of equation (9). C_{im}, W_1 and W_2 had previously been estimated for 32 (P) days. Using these values in equation (9), the dilution factor D was computed to be 0.0019 per day.

DISCUSSION

Water Temperature

Chi-square testing for temperatures at two levels showed homogeniety. Figure 5 presents cross correlations of temperatures between two levels for up to 30 h lags. At zero lag, the correlation coefficient was 0.81. Cross-coherence of temperatures between the two levels indicate significant coherences for 15.0, 17.1 and 40.0 to 125.0 h. The average temperatures at both levels were plotted every two hours (see Appendix) and these graphs confirmed the isothermal conditions in the canal. It may therefore be concluded that quasi-isothermal conditions prevailed in the Burlington Canal and consequently an unidirectional flow regime existed.

Water Movements

At both levels, the resulting currents moved towards the lake. On an average, water movements were towards the channel wall for 8%, the harbour for 39% and the lake for 53% of the time.

Autospectra of Water Movements and Temperature

Autospectral analysis of the currents (Table 2) indicates similar significant periods at both levels. The 12.0 h period may be related to the semidiurnal or tidal motions and this periodicity occurs at both levels along the canal axis and at the upper level only across the canal axis. The 12.1 h period for the temperature (composite value at upper and lower levels) indicates the semi-diurnal or tidal effects on water temperatures. A period of 10.9 h was observed in the temperatues at the upper level and this may be due to the lakewide effects. Kohli and Palmer (1973) found similar periodicities at Lakeview, Lake Ontario.

The first mode of Lake Ontario oscillations (5.0 h) is observed in the Burlington Canal at both levels for currents as well as water temperatures. Rao and Schwab (1974) computed the first mode of oscillations for Lake Ontario as 5.11 h while Rockwell (1966) obtained a value of 4.91 h. The second mode (3.11 h) as computed by Rao and Schwab (1974) may be observed as 3.2 h in the currents and temperatures at the upper level (Table 2). The period of 2.4 h observed in the current along the canal axes at both levels and for temperatures at the upper level may be due to the third free oscillations of Lake Ontario (Rockwell, 1966 and Rao and Schwab, 1974), Helmholtz mode for Hamilton Harbour (Freeman et al, 1974), or a resonant cooscillation involving both.

The periodicities of the measured data relate to the theoretical lake, harbour and Helmholtz periodicities, confirming that the data set used for the mass exchange computation portrays the expected periodic motion.

Mass Exchange

There exists a critical excursion distance below which the water movements in the canal do not clear the confines of the channel. In order to evalute such a critical excursion distance, a DS budget for the harbour was computed. Figure 9 shows that during the 32 days (August 15 to September 16, 1975), 12872 T of DS must leave the harbour through the Burlington Canal. Figure 10 shows that the maximum (11625 T) amount of DS moves through the canal from the harbour to the lake if the flows corresponding to excursions <325 m are ignored. Thus, the critical excursion distance may be about 325 m. This critical distance was also confirmed by Figure 7 which showed the excursions <325 m may, at the most, contribute 16% of the total flow. Based on a critical excursion distance of 325 m, average flow towards the harbour was 9 $m^3.s^{-1}$ (0.27% of harbour volume per day) while towards the lake, it was 25 $m^3.s^{-1}$ (0.77% of harbour volume per day). This resulted in a total mass exchange of 34 $m^3.s^{-1}$ or 1.04% of harbour volume per day (see Table 5). The net flow towards the lake was, therefore, 16 $m^3.s^{-1}$ or 0.5% of harbour volume per day. The mass exchange resulted in a dilution factor of 0.0019 per day.

During the period of no thermal stratification, Palmer and Poulton (1976) estimated a net exchange of 1% of the harbour volume per day towards the lake. These results are similar to the present study. The present episode method yielded relatively better flow estimates validated by the DS budget.

CONCLUSIONS

The mass exchange between Lake Ontario and Hamilton Harbour through Burlington Canal was found to be a complex time variant process. Uni-directional flow and unstratified water in the canal were the basic assumptions of the present study which was based on data for September, 1975. It is estimated that on the average 2.14×10^6 $m^3.d^{-1}$ of harbour water flowed into the lake, while 0.77×10^6 $m^3.d^{-1}$ of lake water flowed into the harbour. This accounts for a total exchange of 1.04% of harbour volume per day with a net water mass exchange of 0.50% of the harbour volume per day towards the lake.

The lake harbour exchange resulted in a dilution of 0.0019 per day. This is very important for maintaining water quality in the harbour because the harbour water, with its higher dissolved solids content, is discharged to the lake while better quality and oxygenated lake water flows into the harbour.

As the calculations for mass exchange were computed for 13 days only and since they are based on the simplifying assumptions of unidirectional flow, they provide only partial information for numerical modelling of the harbour and estimating the dissolved oxygen stocks. Refinements would require collecting data for more points and under stratified conditions and possibly improving the computation technique.

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TABLE 1: Summary of Current Statistics in Burlington Canal, Hamilton Harbour, Lake Ontario, September 1975

	UPPER LEVEL	LOWER LEVEL
Resultant direction coming from 0° as north	252	255
Resultant speed (cm. s^{-1})	3.27	1.76
Average speed (cm. s^{-1})	8.23	7.94
Maximum speed (cm. s^{-1})	44.94	44.23
Persistence factor	0.40	0.22
Period of negligible* speed (% of recording period)	20	20
Percentage of time going in direction of resultant	37	19
Percentage of time going in direction opposite to resultant	7	7
Total number of readings	3925	4309
Interval of readings (mins)	10	10
Total depth of the Canal (m)	9.5	9.5
Depth of the meter operation from bottom (m)	7.5	6.1

* <0.3 cm. s^{-1}

TABLE 2: Summary of Major Spectral Periods (hours)
Burlington Canal, Hamilton Harbour
Lake Ontario
September 1975
80% Confidence Level

	Upper Level	Lower Level
Currents Along the Canal Axis	12.0^*, 5.0^*, 3.2^*, 2.4, 2.3	12.0^*, 5.0^*, 3.4^*, 2.4
Currents Across the Canal Axis	12.0^*, 5.0^*, 3.2	3.9
Temperature-Grand Mean	10.9^*, 5.0^*, 3.2^*, 2.4, 2.2	13.3^*, 5.5^*, 3.3^*

* 95% Confidence Level

TABLE 3 :   Summary of Coherences (95% Confidence)
Burlington Canal, September 1975

Upper (111A) and Lower (1110) Meter Locations

	Significant Periods (h)
Speed along the Canal	3.2
Speed across the Canal	NONE
Lower – speed along Canal and water temp	12.0-10.0, 6.0-4.6, 3.9-3.4, 2.9
Lower – speed across Canal and water temp	NONE
Temp at Upper and Lower locations	120.0-40.0, 17.1-15.0[*]

[*] 90% Confidence

Table 4: Flow through Burlington Canal, Hamilton Harbour.

i	Mean Excursion Travelled E_i (m)	Flow x 10^3 m^3 to harbour H_i	to lake L_i	Exchange T_i	Accumulated Flow x 10^3 m^3 to harbour	to lake Lq_i	Exchange Tq_i	Average Accumulated Flow/day x 10^6 $m^3 \cdot d^{-1}$ to harbour	to lake	Total Exchange
1	1050	0	2358	2358	0	2358	2358	0.00	0.18	0.18
2	950	0	1508	1508	0	3866	3866	0.00	0.30	0.30
3	850	661	1447	2108	661	5313	5974	0.05	0.41	0.46
4	750	1790	3053	4843	2451	8366	10817	0.19	0.64	0.83
5	650	2224	6387	8611	4675	14753	19428	0.36	1.14	1.50
6	550	864	3412	4276	5539	18165	23704	0.43	1.40	1.82
7	450	2507	6832	9339	8046	24907	33043	0.62	1.92	2.54
8	375	881	1554	2435	8927	26551	35478	0.69	2.04	2.73
9	325	1035	1330	2365	9962	27881	37843	0.77	2.15	2.91
10	275	1834	1110	2944	11796	28991	40787	0.91	2.23	3.14
11	225	1608	1695	3303	13404	30686	44090	1.03	2.36	3.39
12	175	1265	983	2248	14669	31669	46338	1.13	2.44	3.57
13	125	836	530	1366	15505	32199	47704	1.19	2.48	3.67
14	75	546	218	764	16051	32417	48468	1.24	2.49	3.73

Table 5 : Summary of Mass Exchange Results Burlington Canal, Hamilton Harbour, Lake Ontario September 1-13, 1975.

For 13 days and excusions	> 325 m
Total flow into harbour	$= 9.96 \times 10^6$ m^3
Total flow into lake	$= 27.88 \times 10^6$ m^3
Total volume of Hamilton Harbour	$= 2.80 \times 10^8$ m^3
Average daily flow into harbour	$= 0.77 \times 10^6$ m^3.d^{-1}
	$= 8.87$ m^3.s^{-1}
	$= 0.27\%$ of harbour volume per day
Average daily flow into lake	$= 2.14 \times 10^6$ m^3.d^{-1}
	$= 24.87$ m^3.s^{-1}
	$= 0.77\%$ of harbour volume per day
Total daily exchange	$= 2.91 \times 10^6$ m^3.d^{-1}
	$= 33.69$ m^3.s^{-1}
	$= 1.04\%$ of harbour volume per day
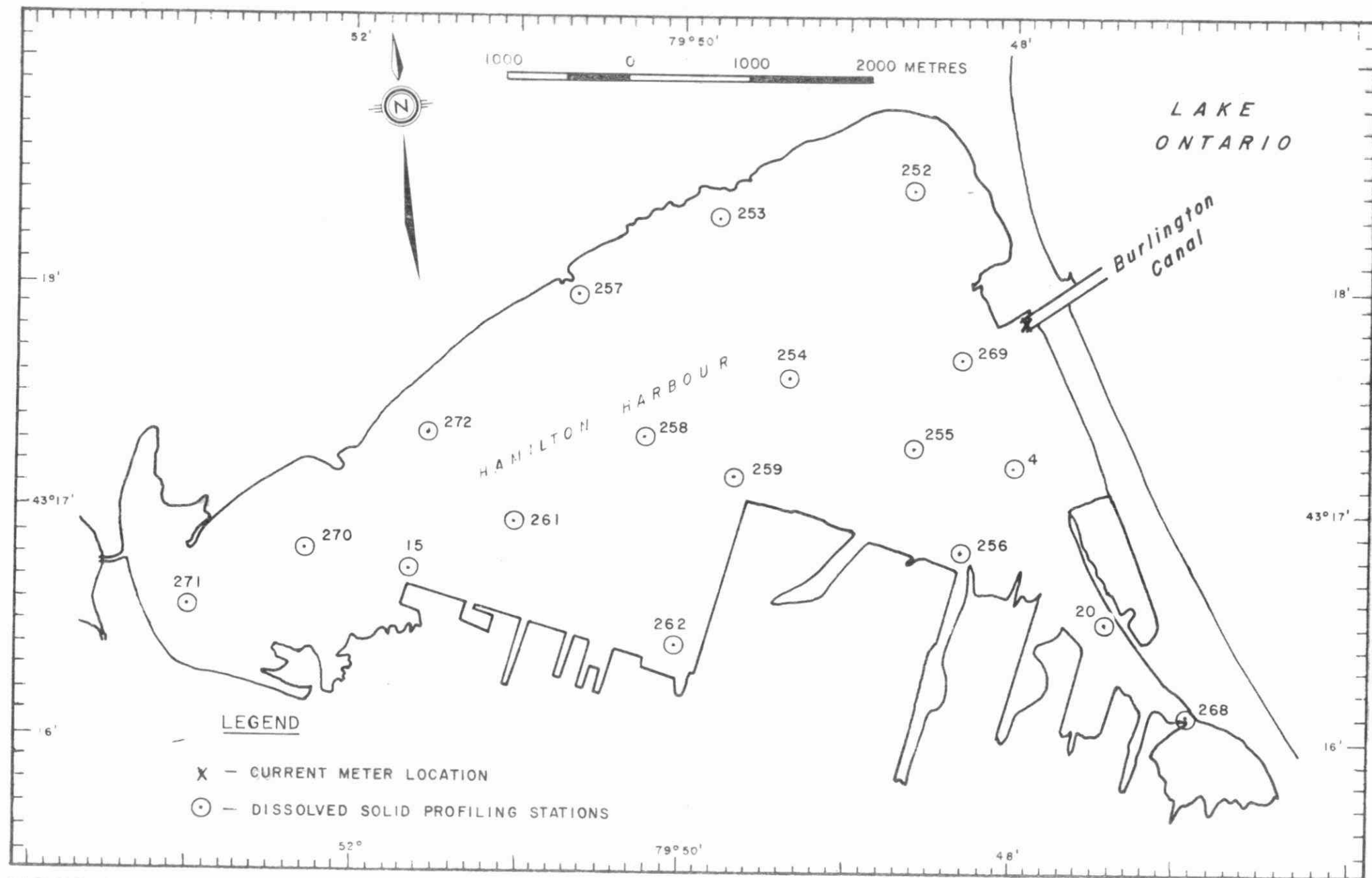
FIGURE 1: HAMILTON HARBOUR AND BURLINGTON CANAL
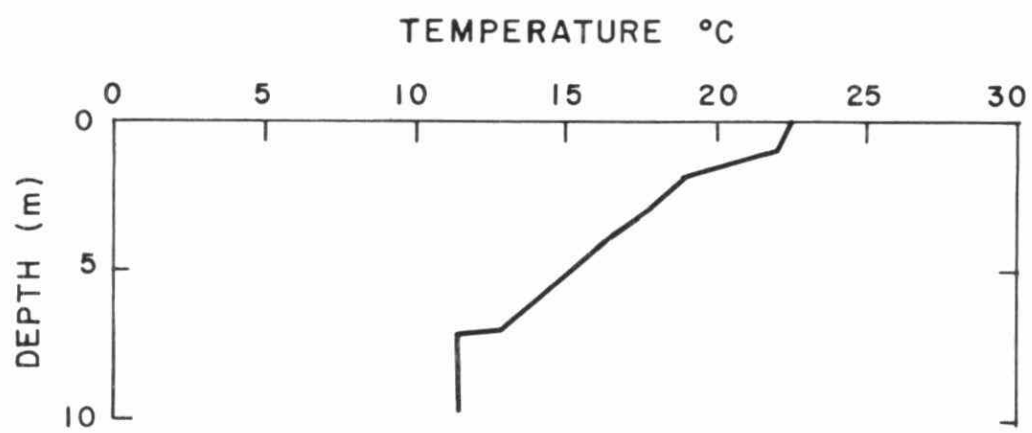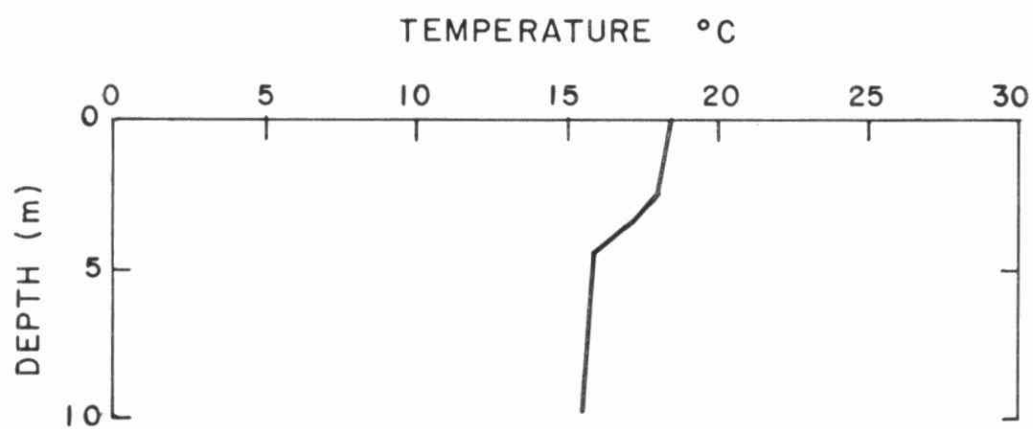
FIGURE 2 : TEMPERATURE PROFILE BURLINGTON CANAL LAKE ONTARIO, 1975
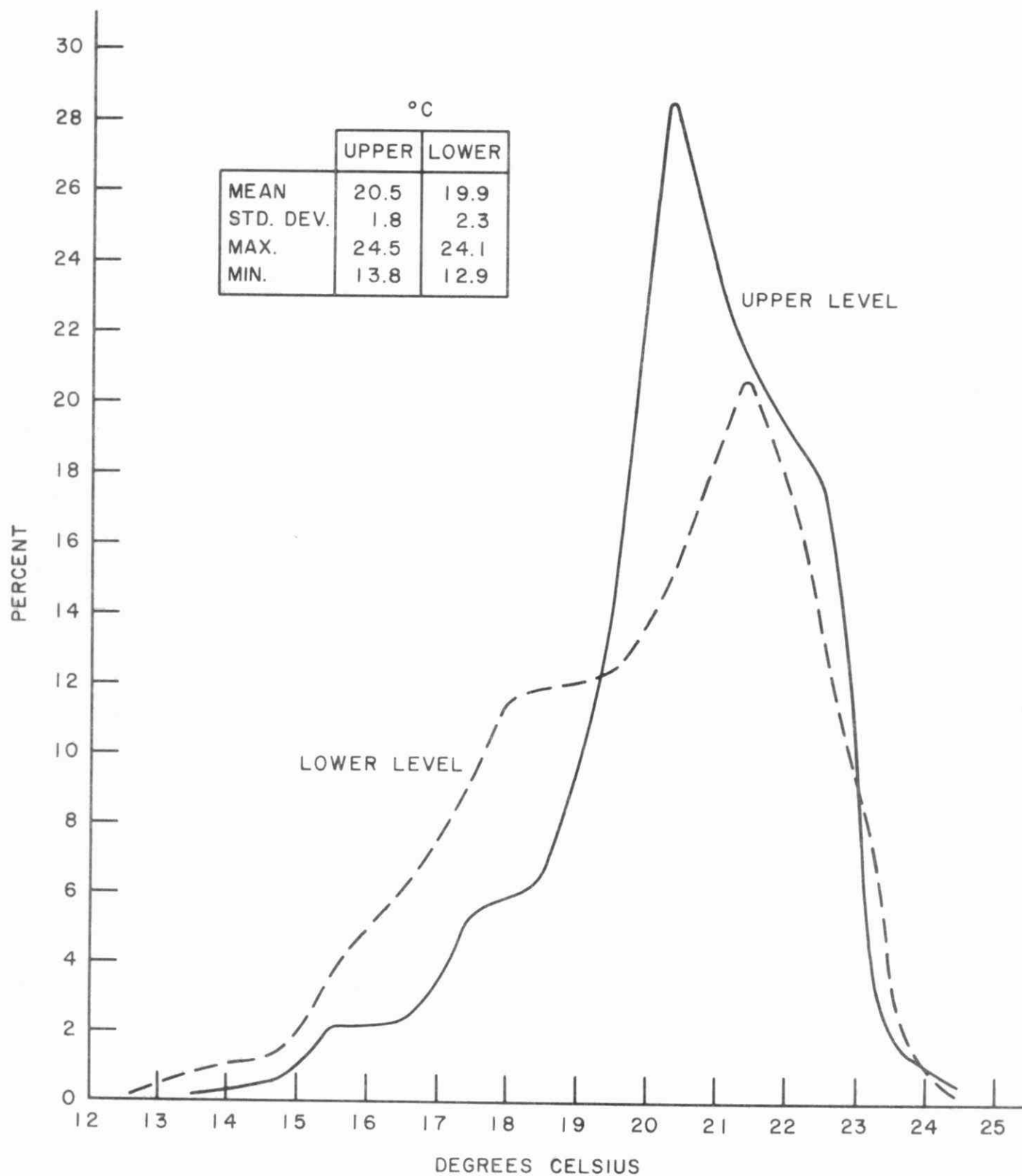
FIGURE 3 — WATER TEMPERATURE; PERCENTAGE OF OCCURRENCE. BURLINGTON
CANAL, HAMILTON HARBOUR, LAKE ONTARIO SEPTEMBER 1975.
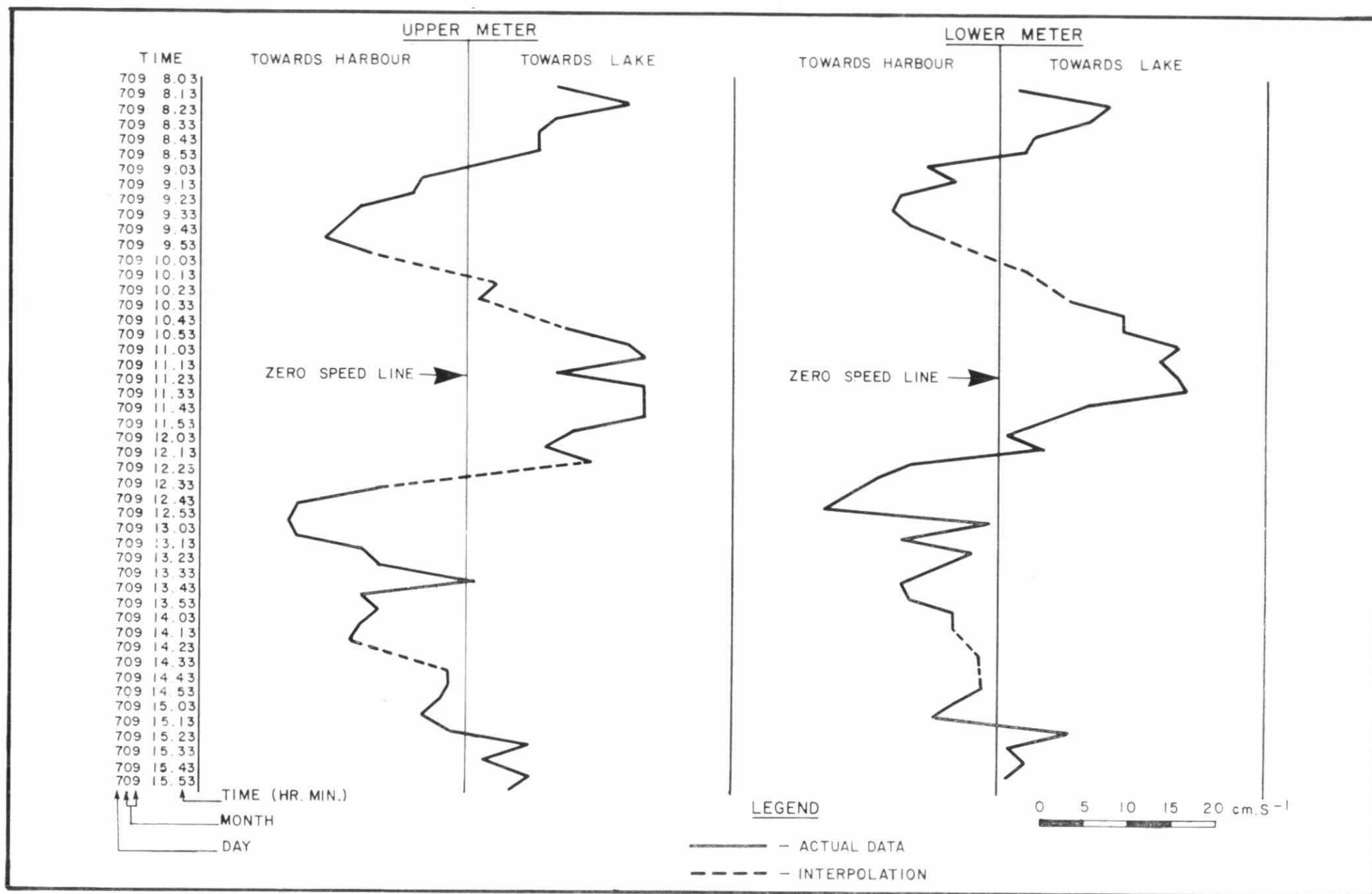
FIGURE 4 : TIME HISTORY OF CURRENTS RESOLVED ALONG BURLINGTON CANAL, LAKE ONTARIO, 1975

F-24
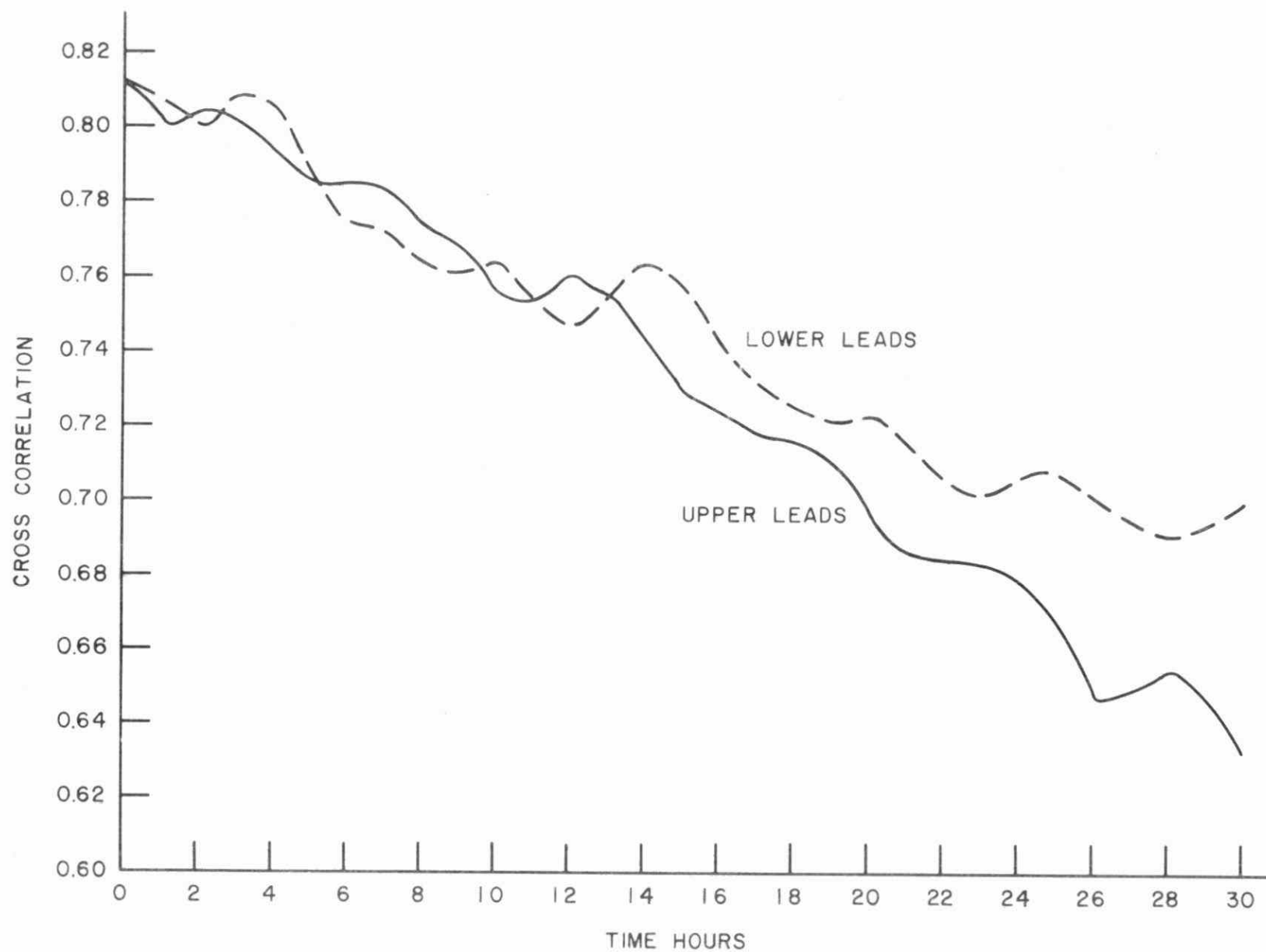
FIGURE 5 — CROSS-CORRELATIONS BETWEEN WATER TEMPERATURES AT TWO DEPTHS,
BURLINGTON CANAL, LAKE ONTARIO, SEPTEMBER 1975.

A

150m

IIIO ✳ IIIA

HARBOUR

LAKE

820m

PLAN

A

2.1m

✳ IIIA
✳ IIIO

7.5m

6.1m

9.5m

107m

SECTION A-A

LEGEND

✳ - CURRENT METER LOCATIONS

✦ - TRANSPOSED DATA LOCATION

ALL DIMENSIONS ARE APPROXIMATE
AND NOT TO SCALE.
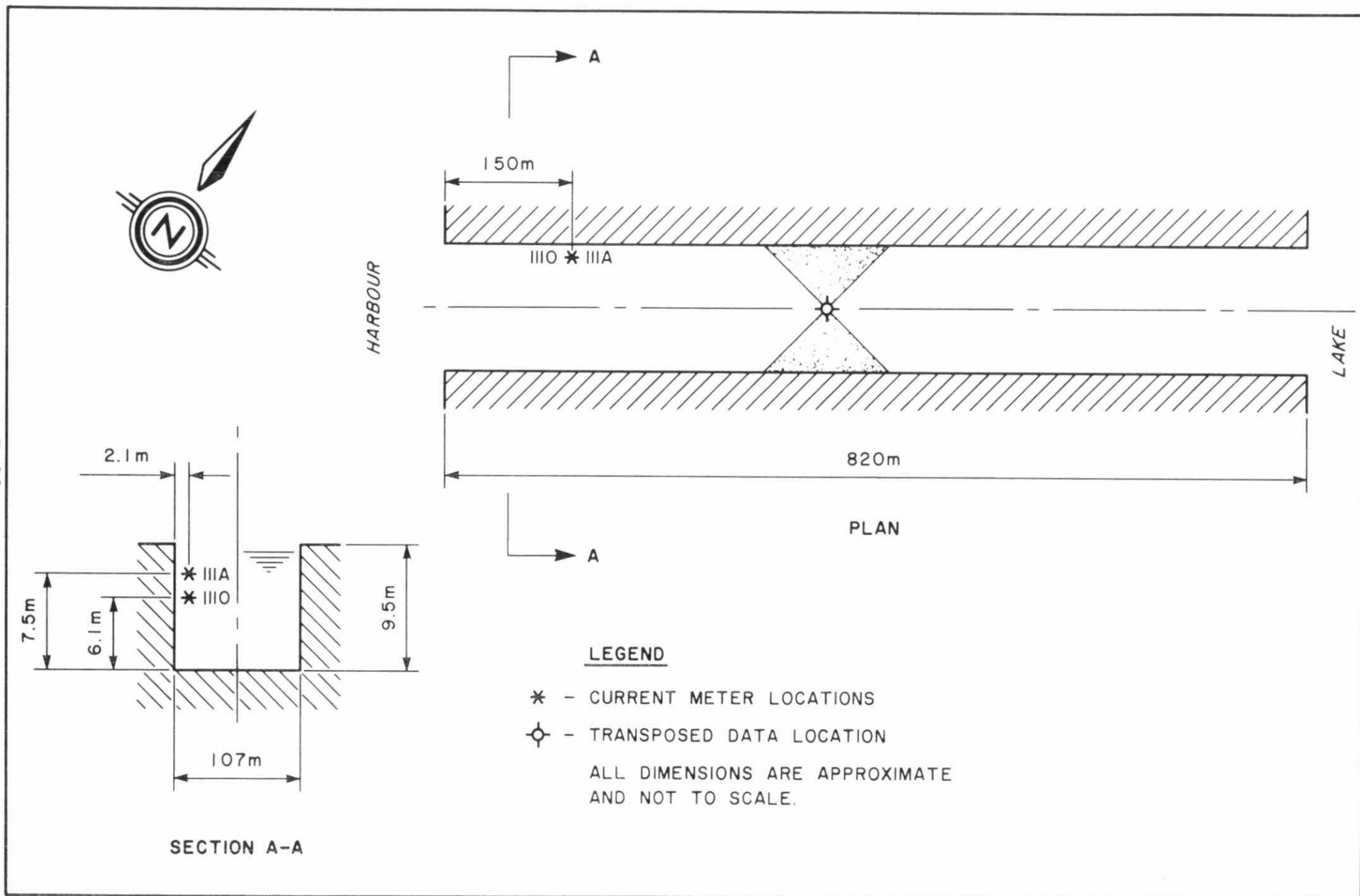
FIGURE 6 - BURLINGTON CANAL
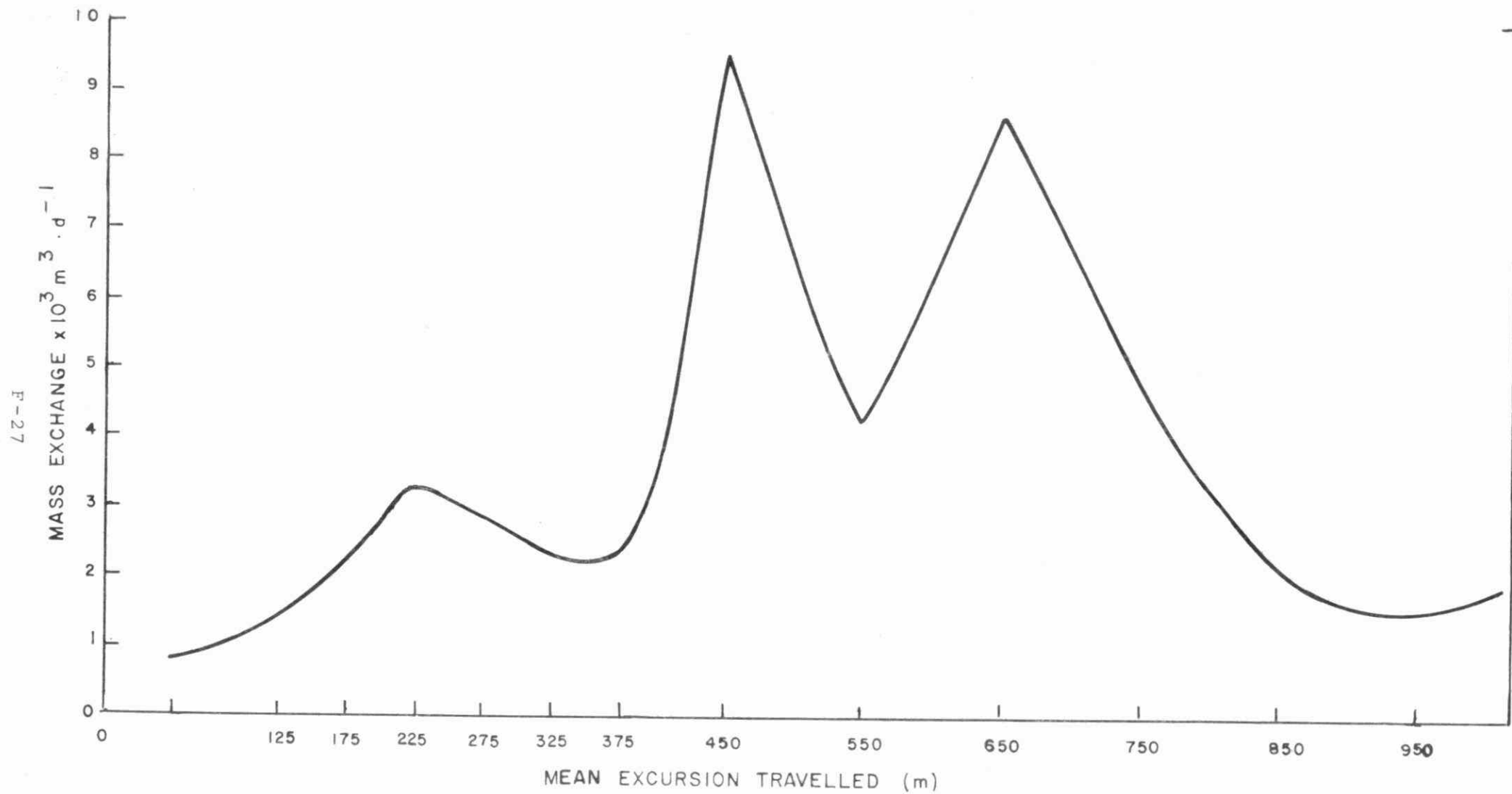
FIGURE 7 : MASS EXCHANGE THROUGH BURLINGTON CANAL, LAKE ONTARIO, SEPTEMBER 1975

F-27

Industrial Uses
$2 \cdot 33 \times 10^6 \, m^3 \cdot d^{-1}$

Rain And Other
Unknown Sources
$0 \cdot 74 \times 10^6 \, m^3 \cdot d^{-1}$

Municipal Discharge
$0 \cdot 28 \times 10^6 \, m^3 \cdot d^{-1}$

Natural Drainage
$0 \cdot 35 \times 10^6 \, m^3 \cdot d^{-1}$

Harbour Vol $= 2 \cdot 8 \times 10^8 \, m^3$

$2 \cdot 14 \times 10^6 \, m^3 \cdot d^{-1}$

$0 \cdot 77 \times 10^6 \, m^3 \cdot d^{-1}$

Burlington
Canal

LAKE ONTARIO

HAMILTON HARBOUR

0   1   2 $3 \times 10^6 \, m^3 \cdot d^{-1}$ SCHEMATIC DIAGRAM

Flow Scale
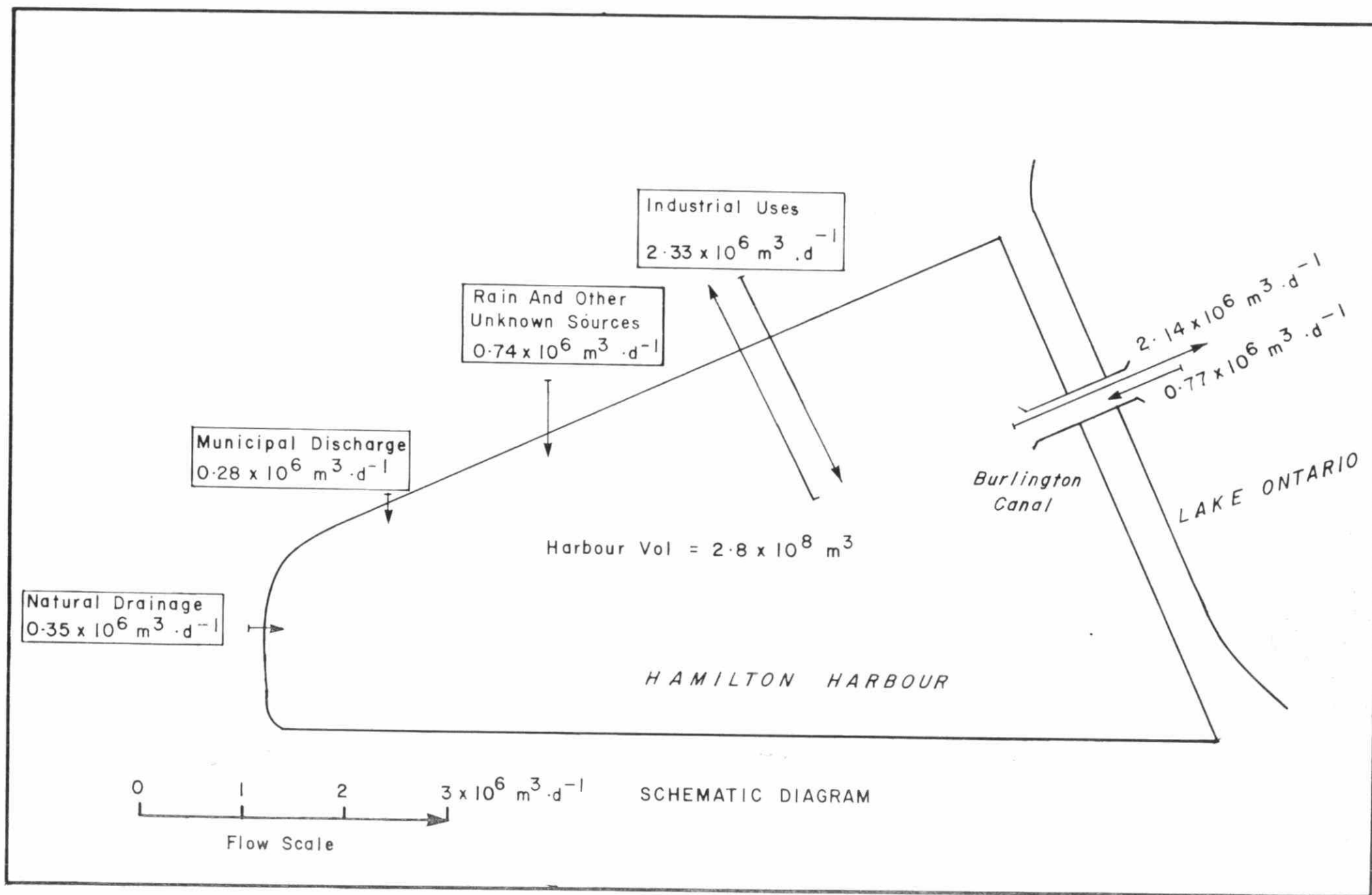
FIGURE 8 : MASS BALANCE OF HAMILTON HARBOUR, LAKE ONTARIO 1 — 13 SEPTEMBER, 1975
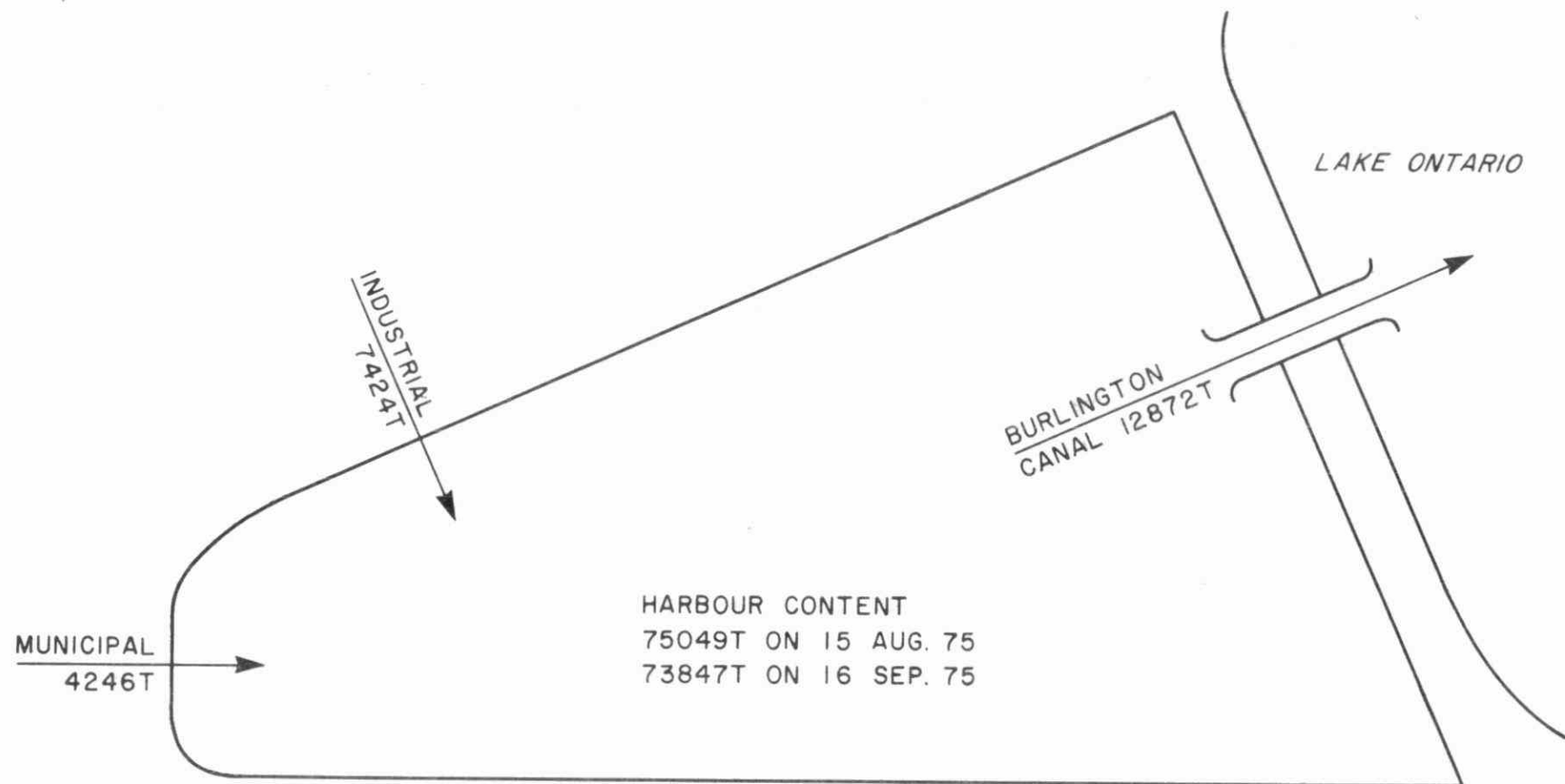
FIGURE 9 - DISSOLVED SOLIDS BUDGET, HAMILTON HARBOUR, AUGUST 15 - SEPTEMBER 16, 1975 (32 DAYS).
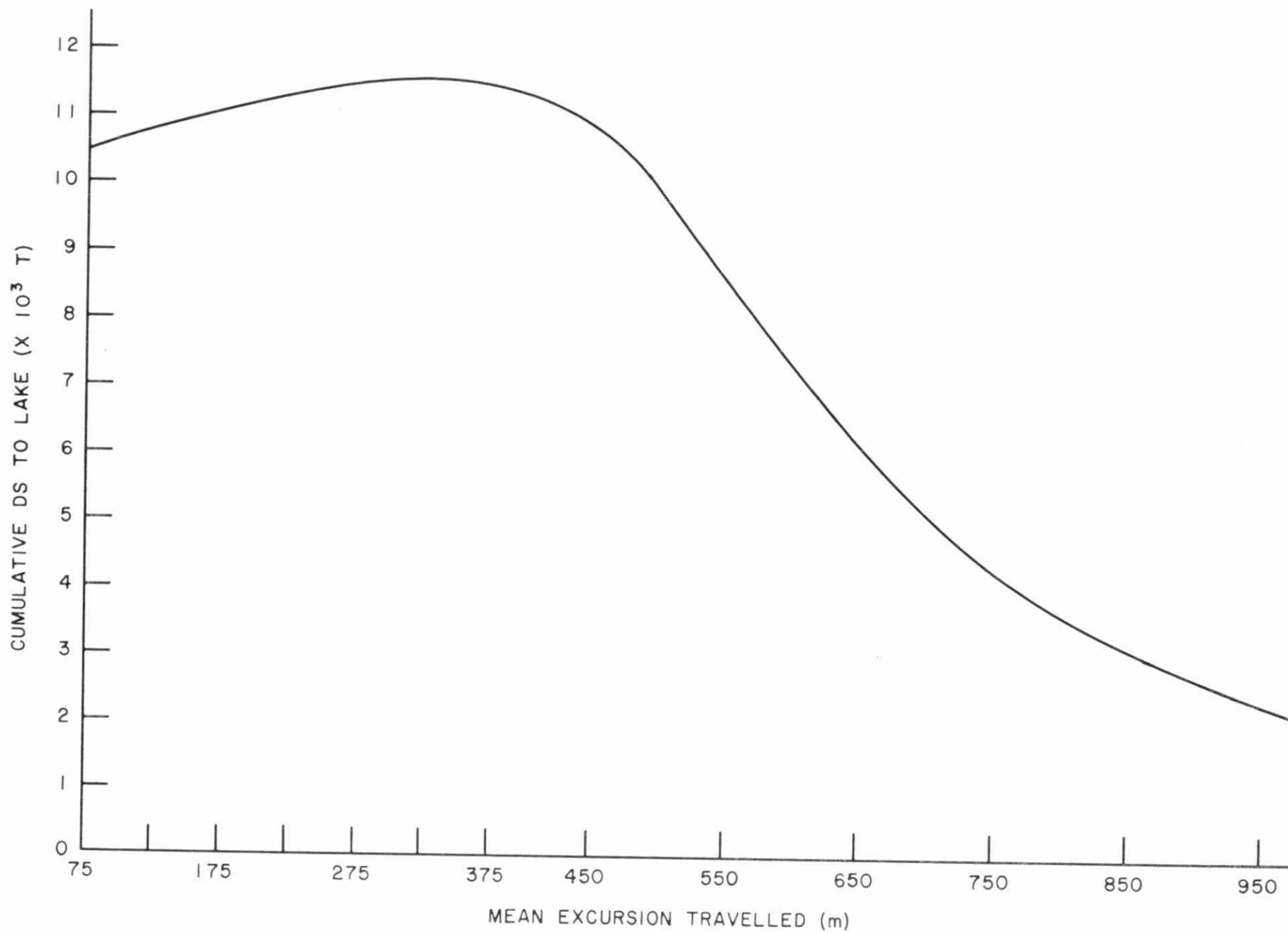
FIGURE 10 — NET TRANSFER OF DISSOLVED SOLIDS (DS) TO LAKE ONTARIO. AUG. 15 — SEPT. 16, 1975.

HAMILTON HARBOUR STUDY 1976

SECTION G

PHYSICAL PROCESSES

HAMILTON HARBOUR PHYSICAL PROCESSES

SUMMARY

Physical processes in the harbour and Burlington Canal were studied
by operating current instruments from 1972 to 1975.

At the mid harbour locations, the net currents were towards the
north during the unstratified period of winter. Under the ice-cover
of Dec 72 - Jan 73, faster water movements were observed at the
deeper location due to the restriction of ice-cover. The monthly
resultant currents varied from 0.4 to 3.1 cm s^{-1} while the
arithmetic average currents were 0.8-4.1 cm s^{-1}. Generally,
faster currents were observed in the Ottawa Street Slip but slower
water movements existed at the Redhill Creek locations.

High currents of up to 144 cm s^{-1} were recorded in Burlington
Canal. Simple average current speed yields a mass exchange of 2-3
times larger than the results computed by the excursion - episode
method.

The spectral periodicities of the currents indicate the presence of
lakewide as well as local harbour influences on the water
movements. Integral length scale of 0.4 to 7.7 m was computed at
the mid harbour location. These length scales are useful in
predicting the physical size of the phytoplankton patches.

HAMILTON HARBOUR PHYSICAL PROCESSES

INTRODUCTION

Physical processes were studied in Hamilton Harbour, as part of the water quality study undertaken by the Ontario Ministry of the Environment (MOE) commencing in the Spring of 1972. MOE recognized the importance of biological, chemical and physical processes and their interactions on the harbour water quality in a dynamic environmental system (MOE, 1974, 1975 and 1977). Oxygen depletion in the deeper waters of the hypolimnion is a major concern during the summer period. Polak and Haffner (1978) showed that mass exchange between the Harbour and the lake, through Burlington Canal, was a major source of dissolved oxygen (DO) in the harbour. Kohli (1977) computed the total lake-harbour exchange to be 1% of the harbour volume per day while the net exchange toward the lake was about 0.5% of the harbour volume per day.

Hamilton Harbour is a natural harbour containing 280×10^6 m^3 of fresh water (MOE, 1974) with a mean depth of 13 m. It is located in the northwest corner of Lake Ontario. It is an active port supplying the needs of the heavy industries on the southern shores. This industry uses and recirculates 27 m^3 s^{-1} (0.83% of harbour volume per day) of harbour water. Municipal sewage outfalls discharge 3.2 m^3 s^{-1} (0.10% of harbour volume per day) of treated effluents to the harbour while several creeks add 4.1 m^3 s^{-1} (0.12% of harbour volume per day).

While some physical data have already been reported (MOE, 1974, 1975 and 1977; Kohli, 1977), this report presents and discusses all physical data collected in Hamilton Harbour and Burlington Canal during 1972-75.

Table 1 lists the details of current meter operations in Hamilton Harbour and Burlington Canal during 1972-75. All meters were operated in the epilmnion except at locations 112 and 113 which

were operated in the hypolimnion. All data (see Appendix 1) collected were numerically smoothed and then partitioned into monthly data set (records). Statistical analyses of water velocities and temperatures were performed to determine the spatial and temporal characteristics. Hourly values of current speed along the two major compass directions were resolved and then subjected to spectral analysis to help identify the physical mechanisms associated with the water movements.

Integral length scale (Λ) is a measure of the statistical or correlation distance between velocities at two points. Λ can be computed by utilizing the variance density function E_n corresponding to the frequency (n) as obtained by the spectral analysis (see Appendix 1). Hinze (1959; p.166) considers wave number (k)

$$k = 2\pi n/\bar{U} \quad\dots\dots\dots\dots\dots\dots\dots \quad (1)$$

instead of the frequency (n) where $\bar{U}$ is the measure of the velocity field. An energy spectrum function E_k was also introduced such that

$$E_k = \bar{U} E_n/2\pi \quad\dots\dots\dots\dots\dots\dots \quad (2)$$

Λ was then computed as

$$\Lambda = (\pi/2S^2) \int_0^\infty (E_k/k)dk \quad\dots\dots\dots\dots \quad (3)$$

where S is the rms (root mean square) value of the velocity field (see Appendix 1 for details). Dispersion is a function of the integral length scale (Λ) and turbulence.

RESULTS

Currents

The resultant current velocity vectors during 1972-75 are presented in Figure 1, and Table 2 summarizes the statistical characteristics

of water currents in Hamilton Harbour. The resultant currents in
the harbour were predominantly going towards the north for ten out
of thirteen times. Figure 1 shows that the resultant currents at
the mid harbour locaions (113 in hypolimnetic and 114 in epilimnetic
waters) were oriented towards the north during the unstratified
period of winter. However, the resultant currents in epilimnetic
water during the stratification of August and September 1975 were
towards the south and then changed towards the west during October
1975. At the harbour locations (113, 114, 116 and 118) the
resultant current magnitudes varied from 0.4 to 3.1 cm s^{-1} and the
arithmetic average speeds ranged between 0.8 and 4.1 cm s^{-1}. The
persistence factors were 0.23-0.79. Kohli (1978) found resultant
currents in the middle of Toronto Harbour to range from 1.1 to 2.8
cm s^{-1} with the persistence factors being 0.30 to 0.68. Figure 1
and Table 2 show that the currents were generally faster (4.5 to 6.4
cm s^{-1}) out of the Ottawa Street slip (location 115) with the
persistence factor of 0.93 to 0.95. The high persistence and faster
currents going out of the slip may be attributed to the average
industrial discharge of 14 m^3 s^{-1} into the slip.

Current measurements at two different depths (locations 113 and 114)
from a single tower revealed faster water movements at the deeper
location (113) during Dec 72 and Jan 73 (see Figure 1 and Table 2).
Surface waters normally have larger magnitude currents due to
surface wind stress, however, during the period of ice cover, the
reverse was found. The ice-cover formed by mid December 1972 and
persisted weil beyond the end of January 1973 when instruments were
removed from the harbour. During the winter, the top layer of
Hamilton Harbour freezes over the warmer subsurface waters. The
frozen layer acts as a restriction to the deeper waters and results
in faster water motions.

Table 3 summarizes the important current statistics in the
Burlington Canal during 1972-75. The resultant currents varied from
1.1 to 15.1 cm s^{-1}, and the arithmetic average speed ranged
between 7.6 and 56.2 cm s^{-1}. The maximum speed recorded in the

channel was 144 cm s^{-1}. The relatively faster currents may be
attributed to the general constriction (van de Kreeke, 1976) and
Helmohtz mode of the harbour (Kohli, 1977). Figure 2 shows the
resultant current vectors in the Burlington Canal during 1972-75.
In Sept 72, Nov 72 and May 73, the resultant currents were going
towards the channel wall. This is rather misleading due to the
bimodal nature of currents (see Appendix 1 for detailed explanation).

Table 3 presents the mean speed going toward the harbour and the
lake with the corresponding percentages of occurrence. These can be
utilized to obtain a rough estimate of water flowing in either
direction. During Sept 75, a rough flow estimate as above resulted
in 4.3 x 10^6 m^3 d^{-1} towards the lake and 2.4 x 10^6 m^3 d^{-1}
towards the harbour. These flow estimates are about 2 to 3 times
larger than those computed by the excursion-episode method (Kohli,
1977) which eliminates the episodes not clearing the channel. The
excursion-episode method therefore provides a better estimate of
flow through the connecting channel. Mass exchange through the
Burlington Canal has not been included in this report since for most
periods, data are available at a single point only. A good data-set
was available at two levels for a reasonable mass exchange
computation during September 1975 and this has been reported (Kohli,
1977) separately.

Water Temperature

Table 4 presents a one-dimensional water temperature frequency of
occurrence in the harbour locations during June and July 74. The
mean water temperature at locations 115 and 116 varied from 2.7 to
7.3°C with standard deviations of 1.4 to 2.2°C. The mean water
temperatures at the Redhill Creek location (118) varied from 21.7 to
25.0°C with standard deviations of 1.4 to 2.4°C. Such a wide
difference in the mean water temperatures were due to the instrument
locations, above or below the thermocline and the proximity of
industrial outfalls to the study site. Vertical water temperature

profiles at these locations were not measured during June and July 74. However, the harbour waters are known to have a thermocline during June and July. The water temperatures at Ottawa Street Slip (115) were measured in the epilimnion (4.0 m from bottom and 4.6 m of water). At site 116, the instrument was also in the epilimnion i.e. 14.6 m from bottom in 18.3 m of water. The location 118 was 5.5 m from bottom in 10.7 m of water and probably in the epilimnion. The high temperatures at this site were due to the industrial discharges of DOFASCO, CIL and Firestone together with the generally stagnant waters of the area.

In Burlington Canal, mean water temperature varied from 9.8 to 24.0°C with standard deviations of 1.8 to 6.7°C (see Table 5) during the months of May to November. The maximum monthly temperature variation of 26°C occurred during Jul 73 at location 111 while the minimum monthly temperature variation was 6°C during Nov 72 at the same site.

Autospectra

The lakewide periodicities (17.1, 15.0, 12.0, 10.0, 8.6, 8.0, 7.5, 7.1, 6.4, 5.7 and 5.5 h) were observed at Hamilton Harbour locations (see Table 6). The periods of 17.1 and 15.0 h each were due to the lakewide seiches. Lunar tides were responsible for the 12.0 h periods observed in the harbour.

The lowest modes of longitudinal free oscillations of Lake Ontario were theoretically computed by Rockwell (1966) as 4.91, 2.97, 2.15, 1.63 and 1.29 h. Rao and Schwab (1974) calculated the lowest modes of free oscillations as 5.10, 3.11, 2.31, 1.87, 1.78 and 1.45 h. Most of these periods were observed in the harbour (see Table 6). The smaller periods of oscillation contribute to variability of harbour currents. Burlington Canal (see Table 7) exhibited a predominant influence of the lunar tides, as 12.0 h periods were observed during most of the study. The periods of 15.0 and 13.3 h observed in many data-sets reflected the lakewide effects of Lake

Ontario. Spectral periods of less than 5 h were found during all
records and may be attributed to the lowest modes of three
oscillations (Rockwell, 1966; Rao and Schwab, 1974). These small
spectral periods are probably due to the local effects of the canal
and contribute to the variability of the water movements in the
canal.

Integral Length Scales

Figure 3 shows a plot of kinetic energy spectrum function E_k and
the wavenumber k for the mid harbour location (114) in the
epilimnion. The plot had a general slope of -3.0 which is similar
to the results of Palmer (1973) in the nearshore area of Lake
Ontario. In Figure 3, as k increased from 0.24 to 14.28 cm^{-1},
E_k decreased rapidily from 9059 to 7.5 $cm^3.s^{-2}$. The value of
(E_k/k) dropped more rapidly with the increase of k. The equation
(3) was numerically integrated between k = 0.24 and 14.28 cm^{-1}.
It was observed that the integration for k 10.0 cm^{-1} yielded no
contribution to the results and therefore may be considered to have
been integrated to k = ∞. The computed integral length scales
(see Table 8) varied from 1.0 to 7.7 m along the north-south
direction and 0.4 to 3.0 m along the east-west direction. Palmer
(1973) computed the integral length scale of 2.4 m for the nearshore
and 4.3 m for the offshore location. The present results are,
therefore considered reasonable. As the scales were computed for
the epilimnion location (114), these may be applicable to the
surface waters. Integral length scales are generally related to the
physical spread of biomass patches of phytoplankton. The length
scales, together with the turbulence of the water, are important
factors in the dispersion characteristics of the water body.

CONCLUSIONS

The resultant currents at the mid harbour locations were towards the
north during the unistratified period of winter. However, the net
current direction in epilimnetic waters during the stratification of
August and September 1975 was towards the south.

The monthly resultant currents in the harbour where predominantly going towards the north and varied from 0.4 to 3.1 cm s^{-1}. The arithmetic, monthly average speed ranged between 0.8 and 4.1 cm s^{-1}. The currents in Ottawa Street Slip were generally faster. During the ice cover in 1972-73, faster currents were observed in deeper waters compared to the currents nearer the ice surface. This phenomenon was related to the restriction of the ice cover.

Burlington Canal recorded high currents of up to 144 cm s^{-1} probably due to the canal restriction. Mass exchange computed from simple average current speeds was found to be 2 to 3 times larger than as computed by the excursion - episode method (eliminating episodes that do not clear the confines of the channel).

Lakewide and semi-diurnal periodicities were observed in the harbour indicating the influence of the lake motions. The harbour also had the lowest 5 modes of Lake Ontario and smaller periods which reflect the influence of the local harbour geometry. Kinetic energy spectra at the mid-harbour locations was similar to those observed in the nearshore areas of Lake Ontario. Integral scale length of 0.4 to 7.7 m was computed from the kinetic energy spectrum at the mid harbour location in epilimnetic waters. These scales may be applicable to the harbour surface waters and useful in determining the physical size of the phytoplankton patches.

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FIGURE I – RESULTANT CURRENTS IN HAMILTON HARBOUR, LAKE ONTARIO, (1972–75).
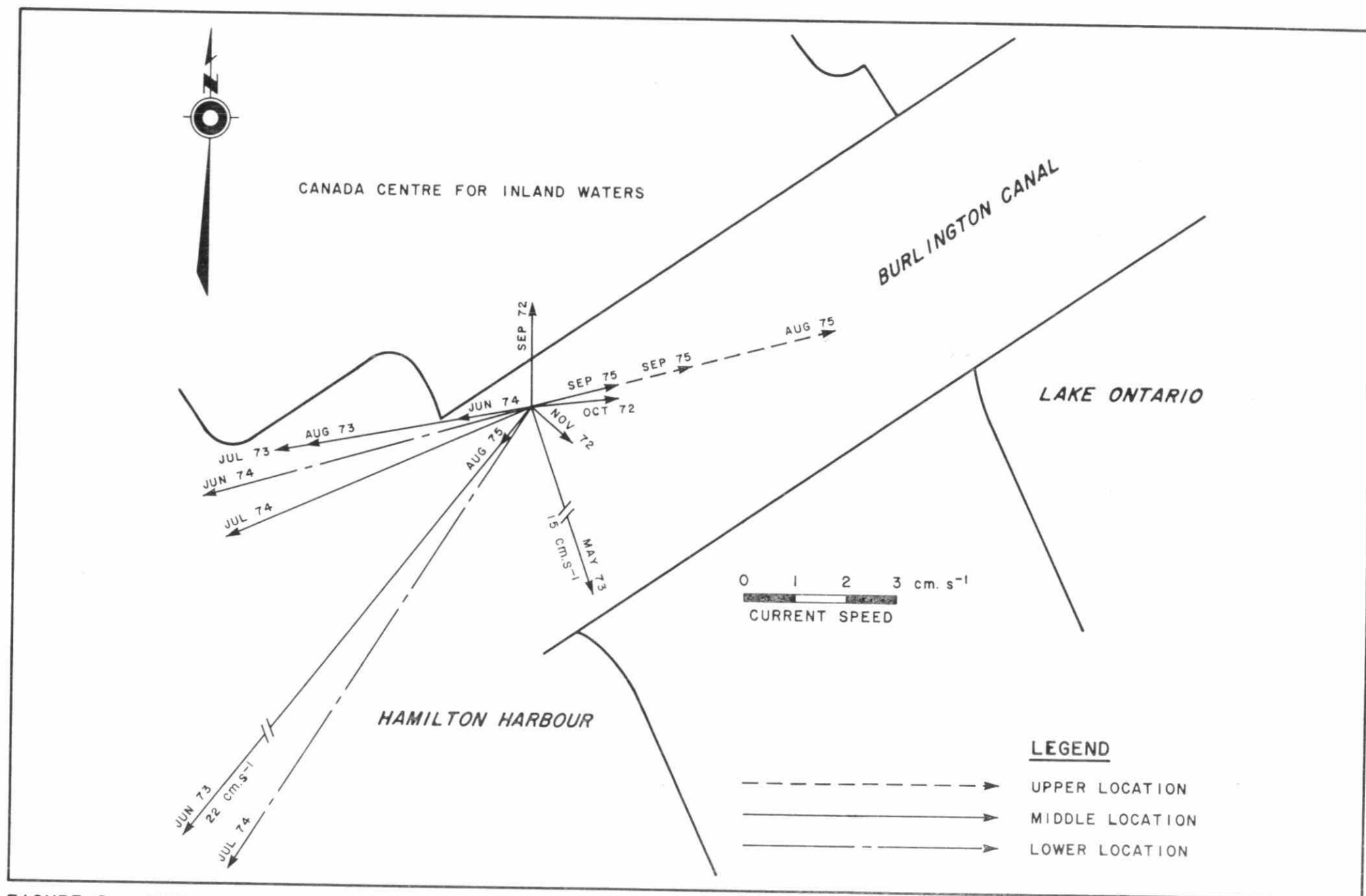
FIGURE 2 - RESULTANT CURRENTS IN BURLINGTON CANAL, (1972-75).
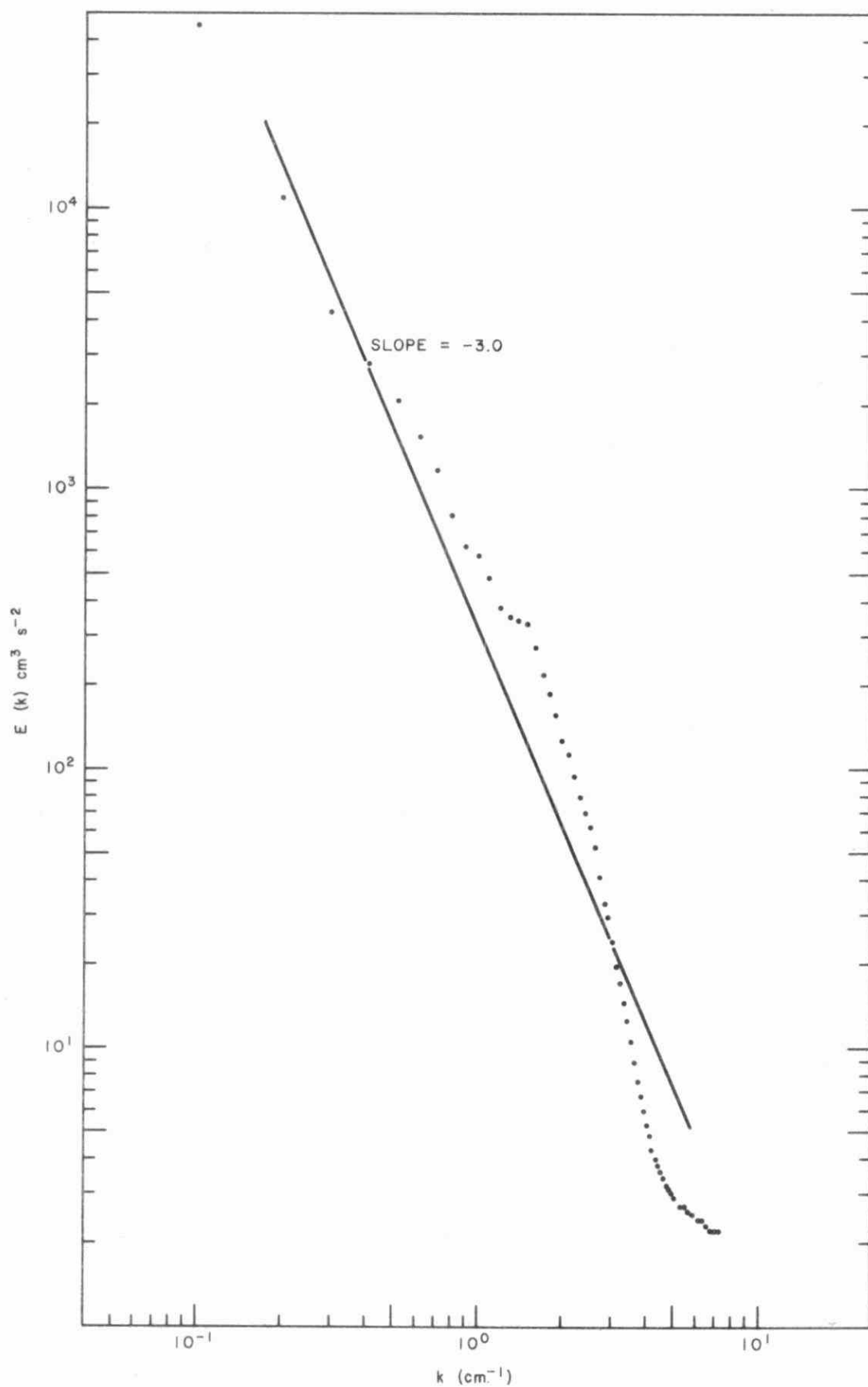
FIGURE 3 — KINETIC ENERGY SPECTRA FOR JAN. 73 HAMILTON
HARBOUR (LOCATION 114)

TABLE 1: Current Instrument Operations in Hamilton Harbour and
Burlington Canal, Lake Ontario 1972-75

Location Code	Instrument Type	Instrument No.	Instrument from Bottom (m)	Total Water Depth (m)	Period of Operation From	Period of Operation To
111	P*	144	6.1	9.4	11 Sep 72	24 Sep 72
					28 Sep 72	2 Nov 72
111	P	206	6.1	9.4	3 Nov 72	10 Nov 72
111	P	164 436	6.1	9.4	4 May 73	22 Aug 73
111	P	239	6.1	9.4	14 Jun 74	22 Jul 74
111	P	207	6.1	9.4	14 Aug 75	30 Sep 75
111A	P	189	7.5	9.4	14 Aug 75	28 Sep 75
112	P	207	2.1	9.4	14 Jun 74	22 Jul 74
113	G**	039	6.1	22.9	15 Dec 72	31 Jan 73
114	G	038	16.3	22.9	14 Dec 72	31 Jan 73
114	G	279	16.3	22.9	7 Aug 75	4 Oct 75
115	G	027	4.0	4.6	14 Jun 74	18 Jul 74
116	G	025	14.6	18.3	14 Jun 74	22 Jul 74
118	P	189	5.5	10.7	15 Jun 74	22 Jul 74

*   Plessey
** Geodyne

All meters were operated in epilimnion except 112 and 113 which were
operated in hypolimnon.

TABLE 2: Summary of Currents in Hamilton Harbour, Lake Ontario 1972-75

| | HAMILTON HARBOUR LOCATIONS | | | | | | | | | | | | |
| | 1 1 3 | | 1 1 4 | | | | | 1 1 5 | | 1 1 6 | | 1 1 8 | |
	Dec 72	Jan 73	Dec 73	Jan 73	Aug 75	Sep 75	Oct 75	Jun 74	Jul 74	Jun 74	Jul 74	Jun 74	Jul 74
Resultant direction coming from $0°$ as North	172	164	172	183	337	304	77	190	190	159	161	166	169
Resultant speed $(cm.s^{-1})$	1.82	3.08	0.41	1.11	0.59	0.48	0.76	6.41	4.46	2.89	1.77	0.97	1.09
Average speed $(cm.s^{-1})$	2.73	4.05	1.76	2.42	2.24	0.84	1.05	6.87	4.69	3.77	3.57	1.04	1.39
Maximum speed $(cm.s^{-1})$	35.17	35.77	9.41	15.09	11.13	9.69	5.38	27.15	17.50	12.67	13.20	8.80	10.55
Persistence factor	0.67	0.76	0.24	0.46	0.26	0.57	0.73	0.93	0.95	0.77	0.50	0.93	0.79
Percentage of negligible* speed (% of recording period)	6	3	2	7	24	52	53					60	48
Percentage of time going in direction of resultant	20	33	12	17	14	22	37	78	87	36	29	33	49
Total number of readings	4896	8929	4971	8929	3600	4320	436	4874	5057	4888	6247	2304	3099
Interval of readings (min)	5	5	5	5	10	10	10	5	5	5	5	10	10

* $< 0.30 \ cm.s^{-1}$

G-15

TABLE 3: Summary of Currents in Burlington Canal, Lake Ontario 1972-75

| | BURLINGTON CANAL LOCATIONS | | | | | | | | | | | 111A | | 112 | |
| | 111 | | | 111 | | | | | | | | | | | |
PERIOD	Sep 72	Oct 72	Nov 72	May 73	Jun 73	Jul 73	Aug 73	Jun 74	Jul 74	Aug 75	Sep 75	Aug 75	Sep 75	Jun 74	Jul 74
Resultant direction coming from $0°$ as North	0	263	312	341	39	80	78	82	66	41	255	260	252	74	33
Resultant speed $(cm.s^{-1})$	2.03	1.74	1.10	15.06	21.73	5.15	4.83	1.48	6.66	1.02	1.76	6.17	3.27	6.70	10.85
Average speed $(cm.s^{-1})$	9.38	10.59	13.87	55.21	56.19	8.85	7.63	8.13	7.80	8.31	7.94	11.78	8.23	10.28	12.54
Max. speed $(cm.s^{-1})$	45.08	122.7	42.59	142.5	143.7	60.08	31.54	42.90	39.75	44.51	44.23	46.50	44.94	40.61	41.25
Persistence factor	0.22	0.16	0.08	0.27	0.39	0.58	0.63	0.18	0.85	0.12	0.22	0.52	0.40	0.65	0.87
Percentage of negligible* speed (% of recording period)	0	1	1	1	0	0	1	3	5	5	20	2	20	2	2
Percentage of time going in direction of resultant	14	37	3	3	49	62	62	46	46	32	24	49	36	12	88
Percentage of time going towards lake	39	50	50	45	28	26	23	37	20	39	46	66	61	6	9
Mean speed going towards lake $(cm.s^{-1})$	8.58	11.69	11.63	41.77	41.35	6.60	5.55	8.87	9.11	8.88	10.86	10.11	7.91	7.76	6.21
Percentage of time going towards harbour	44	45	39	44	58	68	69	59	78	48	39	24	32	91	88
Mean speed going towards harbour $(cm.s^{-1})$	9.12	9.07	14.48	35.94	41.85	8.93	9.35	7.43	10.39	9.21	8.27	9.79	6.63	9.20	10.39
Total # of readings	1844	5045	1032	4027	3888	4464	3167	2248	2448	2588	4309	2591	3965	3102	3103
Interval of readings (mins)	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10

* <0.30 cm.s-1

TABLE 4:   Temperature Frequency, Hamilton Harbour, Lake Ontario 1974

Temperature Range °C		LOCATION				
		115		116		118	
		PERIOD				
		Jun	Jul	Jun	Jul	Jun	Jul
0.00 - 0.99		0.25		6.00	18.57		
1.00 - 1.99		6.25			28.24		
2.00 - 2.99		19.50		0.50	22.05		
3.00 - 3.99		16.00	0.48		14.89		
4.00 - 4.99		24.00	16.14	0.75	5.42		
5.00 - 5.99		17.75	13.25	0.75	0.77		
6.00 - 6.99		16.25	23.86	8.50	0.97		
7.00 - 7.99			30.84	42.50	2.32		
8.00 - 8.99			8.43	33.50	3.68		
9.00 - 9.99			6.99	7.50	3.09		
15.00 - 15.99							
16.00 - 16.99							
17.00 - 17.99							0.78
18.00 - 18.99						4.45	1.96
19.00 - 19.99						3.93	1.76
20.00 - 20.99						20.94	3.33
21.00 - 21.99						34.29	4.89
22.00 - 22.99						20.42	6.46
23.00 - 23.99						8.12	6.65
24.00 - 24.99						7.85	14.48
25.00 - 25.99							21.53
26.00 - 26.99							19.18
27.00 - 27.99							14.68
28.00 - 28.99							3.33
29.00 - 29.99							0.39
30.00 - 30.99							0.59
Mean °C		4.28	6.71	7.33	2.69	21.69	24.98
Std. Deviation °C		1.48	1.44	2.00	2.22	1.40	2.41

TABLE 5:   Temperature Frequency, Burlington Canal, Lake Ontario 1972-75

Temperature Range °C	LOCATION 111											LOCATION 111A		LOCATION 112	
	Sep72	Oct72	Nov72	May73	Jun73	Jul73	Aug73	Jun74	Jul74	Aug75	Sep75	Aug75	Sep75	Jun74	Jul74
0.00 - 3.99		0.12				7.24									
4.00 - 4.99		0.12				1.50									
5.00 - 5.99		0.48				3.01									
6.00 - 6.99		2.40	0.60			2.46									
7.00 - 7.99	0.66	3.37	0.60		0.16	3.14	0.19		0.59					0.50	7.78
8.00 - 8.99	0.66	4.21	4.79	1.35	0.94	2.73	0.77		2.94					1.73	17.51
9.00 - 9.99	0.33	8.65	8.38	6.15	1.40	3.55	0.96	1.00	3.14					6.19	17.51
10.00 - 10.99	0.66	14.78	16.17	9.00	1.87	3.96	2.12	1.25	5.10	0.24				13.61	16.34
11.00 - 11.99	0.66	13.22	26.95	7.65	2.96	4.10	2.69	4.49	6.86	0.24				9.16	13.62
12.00 - 12.99	2.62	5.65	32.93	15.59	4.99	3.83	3.46	4.99	10.39	0.94	0.14			7.43	10.89
13.00 - 13.99	4.59	4.21	4.79	21.29	6.55	4.37	5.38	6.73	16.08	0.94	0.98			6.68	4.09
14.00 - 14.99	4.92	11.06	1.80	25.34	9.67	5.05	7.31	4.99	12.55	1.42	1.12		0.15	7.18	1.36
15.00 - 15.99	10.49	12.98		7.05	9.36	3.83	9.04	13.22	13.92	2.59	3.77		0.31	12.13	1.75
16.00 - 16.99	13.77	13.70		2.25	13.54	3.96	6.15	13.22	11.76	3.54	7.40	0.24	2.16	13.92	1.17
17.00 - 17.99	22.62	5.05		0.60	12.95	5.19	6.73	15.96	8.63	2.83	11.30	0.00	2.16	8.66	0.97
18.00 - 18.99	20.66				12.32	5.87	5.38	14.46	7.43	4.51	8.66	0.24	5.40	4.95	0.19
19.00 - 19.99	15.08				10.76	6.83	9.81	10.97	2.35	10.38	12.15	0.47	6.33	7.43	
20.00 - 20.99	1.97				8.89	6.56	5.19	6.98	0.59	12.03	15.36	5.90	12.69	3.22	
21.00 - 21.99	0.33				2.03	8.47	7.88	1.75	0.59	12.74	20.67	4.48	28.55	0.74	
22.00 - 22.99					1.25	6.15	8.08			11.08	14.66	7.08	21.45		
23.00 - 23.99					0.16	8.20	18.85			14.15	3.49	8.96	18.06		
24.00 - 24.99										14.62	0.28	14.39	2.01		
25.00 - 25.99										4.48		19.34	0.46		
26.00 - 26.99										0.71		17.69			
27.00 - 100.00												17.69			
												3.54			
Mean °C	17.01	12.73	11.81	13.52	16.58	15.11	18.52	16.65	14.34	21.25	19.85	24.03	20.48	13.44	9.82
Std. Dev. °C	2.24	2.78	2.58	3.15	2.98	6.47	4.20	2.62	2.68	2.96	2.28	2.18	1.78	3.35	2.34

TABLE 6:   Summary of Major Spectral Periods (hours)
           80% Confidence Level
           Hamilton Harbour, Lake Ontario

Location	Period	Data Averaged Over (h)	North-South	East-West
113	Dec 72	1	None	None
113	Jan 73	1	None	7.1,3.2,2.5*
114	Dec 72	1	10.0*,4.8*,3.9**, 2.6**,2.4	5.5*,3.9,3.2,2.6,2.2
114	Jan 73	1	12.0,4.0	None
115	Jun 74	1	12.0,3.1*,2.7*, 2.3	12.0,6.0**,4.6*,3.5, 3.0*,2.5,2.2*
115	Jul 74	1	15.0,5.5*,4.0**, 2.4**	4.0**
116	Jun 74	1	15.0,5.5*,4.6*,4.3*, 3.4*,3.2**,2.4	10.0**,5.5,3.8,3.3* 2.6
116	Jul 74	1	8.0,5.2,3.5,2.6	8.6*,7.5*,5.7,4.8
118	Jun 74	½	15.0,6.0,3.7,3.3, 2.6*,1.3,1.1	15.0**,5.5,3.2,1.8,1.4, 1.2,1.0**
118	Jul 74	½	10.0,4.6*,2.8,1.3	2.8,1.5,1.3
114	Aug 75	1	3.0*,2.2	15.0,8.6,4.6,4.1,2.8
114	Sep 75	1	17.1,10.0,7.5,5.5, 4.8	None

*   95% confidence level
**   99% confidence level

TABLE 7:   Summary of Major Spectral Periods (hours)
           80% Confidence Level
           Burlington Canal, Lake Ontario

Location	Period	Data Averaged Over (h)	Along Channel	Across Channel
111	Sep 72	1	12.0*,5.5*,4.3*,3.2*, 2.4*	13.3*,4.8*,3.5,2.8,2.5*
111	Oct 72	1	12.0**,5.0**,3.2**, 2.4**	5.2**,3.2**,2.3*
111	Nov 72	1	3.2,2.1*,1.7,1.5**,1.1*	15.0*,2.1**,1.5**,1.1*
111	May 73	1	15.0,5.2,4.6**,3.0**, 2.4,2.1	15.0**,7.5,4.0,3.5, 3.0**,2.8,2.3*
111	Jun 73	1	10.0,4.6,2.9,2.4	5.2*,3.1,2.5
111	Jul 73	1	12.0**,5.0**,3.2**, 2.4*,2.2	12.0*,5.0**,3.2**,2.4*, 2.1
111	Aug 73	1	12.0**,5.0*,3.2**, 2.3*	12.0**,5.2**,3.2**,2.3
111	Jun 74	1	12.0**,5.0**,3.2,2.5*	12.0**,5.0**,3.2**,2.3**
111	Jul 74	1	12.0**,5.0**,2.3**	12.0**,5.0**,3.2*,2.3**
112	Jun 74	1	12.0,4.6,3.2,2.3	4.6,2.3**
112	Jul 74	1	12.0**,5.0**,3.2,2.4**	12.0**,5.0**,3.2**,2.4**
111A	Aug 75	1	12.0**,4.8**,3.2**, 2.4**	12.0**,4.8**,3.2**,2.4*
111A	Sep 75	1	12.0**,5.0**,3.3**, 2.4**,2.3**	12.0**,5.0**,3.2**,2.4, 2.3**
111	Aug 75	1	12.0**,5.0**,3.2**, 2.5,2.2*	13.3,7.5,3.2**,2.1
111	Sep 75	1	12.0**,4.8**,3.2**, 2.4*	13.3,7.5,5.5,4.8,3.3**

*   95% confidence level
**   99% confidence level

TABLE 8:   Summary of Integral Length Scales (m)

Location 114, Hamilton Harbour

LAG (h)	NORTH - SOUTH				EAST - WEST			
	Dec 72	Jan 73	Aug 75	Sept 75	Dec 72	Jan 73	Aug 75	Sept 75
60	3.73	7.65	1.69	0.98	0.39	0.77	2.33	3.04
40	2.79	5.81	1.40	0.84	0.30	0.64	1.76	2.45
30	2.29	4.81	1.27	0.74	0.24	0.56	1.39	2.05
20	1.71	3.68	1.14	0.60	0.17	0.46	1.00	1.54
Series Length (h)	414	744	600	720	414	744	600	720
Mean Speed (cm s^{-1})	0.40	1.03	0.44	0.19	0.04	0.15	0.22	0.34
RMS Speed (cm s^{-1})	1.00	2.55	2.39	1.03	1.00	4.36	2.44	1.17

APPENDIX 1

The data from all locations were pre-whitened (numerically smoothed)
after Blackman and Tukey (1959; p.29, 39, 74) using binomial weights
after Panofsky and Brier (1968; p.150).

Binomial distribution is generally applied to cases when two
alternatives are possible, e.g. a coin spun can land with either
head or tail. If N coins are spun independently, m heads and (N-m)
tails will show up. Smoothing functions can be made to approximate
the normal distribution curve by making the weights proportional to
the binomial distribution. The smoothing coefficients (C_m) are
computed thus:

$$C_m = N!/m! \ (N-m)! \ \ldots\ldots\ldots\ldots\ldots\ldots \ (1)$$

For data at 5 to 10 min intervals N=4 produced acceptable binomial
coefficients.

The binomial weights (S_m) for smoothing the data series are
obtained as follows:

$$S_m = C_m / \sum_{o}^{m} C_m \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (2)$$

Current speed and direction and water temperature data are smoothed
as above. However, if the instrument is operated in the Burlington
Channel, the direction is not smoothed since the movement in
channels are essentially along the channel axis.

The smoothed data are then partitioned into monthly records. For
each record, a two-dimensional frequency of occurrence of current
speed and direction were computed along with the resultant speed and
direction, mean and maximum current speeds and the persistence. The
current frequency tables along with the above results are presented
in Tables 1.01 to 1.28.

AUTOSPECTRA

Time series can be subjected to spectral analysis to help understand
the physics underlying the variations in the time series by
comparing the significant periods of time variation with the
theoretical values. Statistically significant peaks indicate the
likelihood or otherwise of variations with certain average peaks.
As a prerequisite for spectral analysis, auto-correlation
coefficients of the time series are computed. Auto-correlation
coefficients are ordinary correlation coefficients of two members of
the time series at different time lags.

Let Ui represent the time series. Auto-correlation coefficients may
be computed as (Panofsky and Brier, p.138):

$$r_L = (U_i - \bar{U})(U_{i+L} - \bar{U})/N.s^2 \quad \dots\dots\dots\dots\dots \quad (3)$$

where r_L is the auto-correlation coefficient for the lag L.

$\bar{U}$ is the arithmetic average of the series U_i

N is the number of observations at time interval Δt.

s^2 is the variance of the series

s is the RMS (root mean square) value of the series.

Auto-correlation coefficients are utilized to compute the normalized
spectrum B_i (Panofsky and Brier, p.143) for i = 1 to

$$B_i = (r_o/L) + (r_L/L)(-1)^i + \sum_{J=1}^{L-1} \left[r_J \cos(\pi iJ/L) \right] \quad \dots \quad (4)$$

Equation (4) results in greatly distorted spectral estimates
whenever there are rapid fluctuations in the true spectrum.
Spectral estimates are therefore smoothed by Hanning (Blackman and
Tukey, 1959, p.34 and 171) as follows:

$$A_i = 0.25 \, B_{i-1} + 0.50 \, B_i + 0.25 \, B_{i+1} \quad \dots\dots\dots \quad (5)$$

where A_i are the smoothed normalized spectral estimates.

The frequency (n) corresponding to the spectral estimate is computed as

$$n = i/2L\Delta t \quad \dots\dots\dots\dots\dots\dots\dots\dots \quad (6)$$

and the spectral estimates A_i or A_n are usually plotted against the frequency (n).

In order to determine the statistically significant periods of the spectral analysis the degrees of freedom (ν) associated with the spectrum are computed thus:

$$\nu = (2N-L/2)/L \quad \dots\dots\dots\dots\dots\dots\dots \quad (7)$$

Jenkins and Watts (1968; p.82) plotted the upper and lower limits for α = 0.01, 0.05 and 0.20 and $3 \leq \nu \leq 100$ (see Figure 1.01). The curves can be used to determine an interval within which a spectral peak may be expected to lie on $100(1-\alpha)$ % of occasions.

Palmer (1973) computed an integral length scale at a nearshore and offshore location in Lake Ontario. Integral length scale is a flow property and is a measure of the correlation distance between velocities at two points.

The normalized spectra A_n, is first converted to the energy spectra or variance density spectra E(n)

$$E_n = A_n \times s^2 \quad \dots\dots\dots\dots\dots\dots\dots \quad (8)$$

Hinze (1959; p.54) showed that

$$\int_0^\infty E_n \, dn = s^2 \quad \dots\dots\dots\dots\dots\dots\dots \quad (9)$$

It is convenient to redifine E_n in terms of a wave number k and the kinectic energy spectra E_k such that

$$\int_0^\infty E_k \, dk = s^2 \quad \dots\dots\dots\dots\dots\dots\dots \quad (10)$$

$$E_k = \bar{U} \; E_n / 2\pi \quad \ldots\ldots\ldots\ldots \quad (11)$$

$$k = 2\pi n / U \quad \ldots\ldots\ldots\ldots\ldots \quad (12)$$

The integral length scale (Λ) may be computed that:

$$\Lambda = (\pi / 2 \; S^2) \int_{0}^{\infty} (E_k / k) \; dk \quad \ldots\ldots\ldots\ldots \quad (13)$$

Bimodel Currents

Tables 3, 1.14, 1.16 and 1.17 show that during Sep 72, the currents were actually going towards the harbour (44% of time), the lake (39% of the time) and the resultant direction for a lesser (14%) percentage of time. Similarly, during Nov 72 and May 73, the currents were in the resultant direction for a mere 3% of time while they went towards the harbour for 39 and 44% and the lake for 50 and 45% of the time respectively. In all other cases, the resultant currents were either towards the harbour or the lake and for greater percentages of time (24 to 88%).

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TABLE 1.01

LOCATION CODE : 1130
AREA   : HAMILTON HARBOUR
LAKE   : ONTARIO

PERIOD   : DEC 72
LATITUDE : 43 17 28 N
LONGITUDE : 79 49 56 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50- 22.49	22.50- 67.49	67.50- 112.49	112.50- 157.49	157.50- 202.49	202.50- 247.49	247.50- 292.49	292.50- 337.49	ROW SUMS
0.0 -- 0.30	0.12	0.51	2.27	2.35	0.27	0.55	0.06	0.16	6.29
0.31 -- 1.99	0.51	1.37	15.50	11.11	3.78	4.25	3.64	0.96	41.12
2.00 -- 3.99	0.20	1.06	0.98	8.70	6.99	5.82	2.92	1.10	27.78
4.00 -- 5.99	0.04	0.39	0.14	3.51	4.98	4.78	1.49	0.49	15.83
6.00 -- 7.99	0.0	0.06	0.04	2.53	1.57	0.49	0.08	0.06	4.84
8.00 -- 9.99	0.0	0.0	0.0	1.02	1.53	0.02	0.0	0.02	2.59
10.00 -- 36.99	0.0	0.04	0.04	0.14	1.29	0.02	0.02	0.0	1.55

| COLUMN SUMS | 0.88 | 3.43 | 18.97 | 29.37 | 20.40 | 15.93 | 8.21 | 2.80 | 100.00 |

RESULTANT CURRENT IS   1.82 CM/S AT 172 DEG FROM NORTH   TOTAL NO. READINGS   4896

MEAN CURRENT IS   2.73 CM/S   PERSISTENCE IS   0.67

MAXIMUM CURRENT IS   36.00 CM/S   READINGS TAKEN EVERY 5 MIN

METER OPERATED AT   6.1 M FROM BOTTOM IN 22.9 M OF WATER

TABLE 1.03

LOCATION CODE : 1140
AREA : HAMILTON HARBOUR
LAKE : ONTARIO

PERIOD : DEC 72
LATITUDE : 43 17 28 N
LONGITUDE : 79 49 56 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50–22.49	22.50–67.49	67.50–112.49	112.50–157.49	157.50–202.49	202.50–247.49	247.50–292.49	292.50–337.49	ROW SUMS
0.0 -- 0.30	0.08	0.18	0.12	0.40	0.40	0.24	0.14	0.12	1.69
0.31 -- 0.99	3.04	5.17	5.49	8.01	2.43	3.10	1.75	2.55	31.54
1.00 -- 1.99	2.55	2.41	2.57	12.77	3.12	3.78	4.02	5.49	36.73
2.00 -- 2.99	0.62	1.47	0.89	1.93	2.35	3.22	1.47	1.99	13.94
3.00 -- 3.99	0.32	1.31	0.44	1.21	1.35	1.51	0.38	1.13	7.64
4.00 -- 4.99	0.12	0.56	0.26	0.72	1.29	1.31	0.22	0.48	4.97
5.00 -- 9.99	0.06	0.26	0.08	0.74	0.93	0.95	0.10	0.36	3.48
COLUMN SUMS	6.80	11.37	9.86	25.79	11.87	14.10	8.09	12.13	100.00

RESULTANT CURRENT IS 0.41 CM/S AT 172 DEG FROM NORTH   TOTAL NO. READINGS 4971

MEAN CURRENT IS 1.76 CM/S   PERSISTENCE IS 0.23

MAXIMUM CURRENT IS 9.41 CM/S   READINGS TAKEN EVERY 5 MIN

METER OPERATED AT 16.3 M FROM BOTTOM IN 22.9 M OF WATER

TABLE 1.04

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50–22.49	22.50–67.49	67.50–112.49	112.50–157.49	157.50–202.49	202.50–247.49	247.50–292.49	292.50–337.49	ROW SUMS
0.0 -- 0.30	0.15	0.24	0.55	0.24	1.12	3.68	0.71	0.50	7.18
0.31 -- 0.99	1.10	2.23	1.71	2.25	3.23	8.66	2.63	2.62	24.43
1.00 -- 1.99	0.86	2.62	2.98	3.88	2.65	5.68	2.30	2.53	23.50
2.00 -- 2.99	0.27	1.37	1.16	2.89	2.80	4.05	1.89	1.37	15.80
3.00 -- 3.99	0.17	0.74	0.39	2.32	1.87	2.59	0.88	0.74	9.70
4.00 -- 4.99	0.10	0.60	0.31	1.94	1.15	1.43	0.55	0.40	6.50
5.00 -- 15.99	0.22	0.76	0.45	3.46	3.37	3.26	0.68	0.69	12.90
COLUMN SUMS	2.87	8.56	7.56	16.97	16.19	29.35	9.64	8.86	100.00

RESULTANT CURRENT IS   1.11 CM/S AT 183 DEG FROM NORTH   TOTAL NO. READINGS   8929

MEAN CURRENT IS   2.42 CM/S   PERSISTENCE IS   0.46

MAXIMUM CURRENT IS   15.00 CM/S   READINGS TAKEN EVERY 5 MIN

METER OPERATED AT   16.3 M FROM BOTTOM IN 22.9 M OF WATER

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TABLE 1.05

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50– 22.49	22.50– 67.49	67.50– 112.49	112.50– 157.49	157.50– 202.49	202.50– 247.49	247.50– 292.49	292.50– 337.49	ROW SUMS
0.0 -- 0.30	2.56	3.94	3.92	4.92	1.75	2.78	2.36	1.78	24.00
0.31 -- 0.99	2.47	2.06	2.36	1.22	1.08	1.97	1.78	1.94	14.89
1.00 -- 1.99	3.94	2.31	2.83	0.89	1.22	2.06	2.94	2.58	18.78
2.00 -- 2.99	2.28	1.50	0.94	0.44	1.17	1.19	1.83	1.64	11.00
3.00 -- 3.99	1.67	1.14	0.69	0.33	0.31	0.69	1.11	1.78	7.72
4.00 -- 4.99	0.64	1.31	1.56	0.03	0.33	0.86	1.92	1.31	7.94
5.00 -- 11.99	1.28	2.03	3.67	0.39	0.28	1.00	4.08	2.94	15.67

| COLUMN SUMS | 14.83 | 14.28 | 15.97 | 8.22 | 6.14 | 10.56 | 16.03 | 13.97 | 100.00 |

RESULTANT CURRENT IS   0.59 CM/S AT 337 DEG FROM NORTH   TOTAL NO. READINGS   3600

MEAN CURRENT IS   2.24 CM/S   PERSISTENCE IS   0.26

MAXIMUM CURRENT IS   11.13 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   16.3 M FROM BOTTOM IN 22.9 M OF WATER

TABLE 1.07

LOCATION CODE : 1140   PERIOD   : OCT 75
AREA   : HAMILTON HARBOUR   LATITUDE : 79 49 56 W
LAKE   : ONTARIO   LONGITUDE : 43 17 28 N

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50– 22.49	22.50– 67.49	67.50– 112.49	112.50– 157.49	157.50– 202.49	202.50– 247.49	247.50– 292.49	292.50– 337.49	ROW SUMS
0.0 -- 0.30	3.90	4.36	18.81	0.69	1.61	0.69	20.64	1.83	52.52
0.31 -- 0.99	0.69	5.28	4.36	0.69	0.0	0.0	0.69	0.69	12.39
1.00 -- 1.99	0.0	1.15	3.67	0.0	0.0	0.0	7.80	0.0	12.61
2.00 -- 2.99	0.0	0.46	5.50	0.0	0.0	0.0	0.69	0.0	6.65
3.00 -- 3.99	0.0	0.92	6.88	0.69	0.0	0.0	0.0	0.0	8.49
4.00 -- 4.99	0.0	0.0	4.59	0.0	0.0	0.0	0.0	0.0	4.59
5.00 -- 5.99	0.0	0.0	2.52	0.0	0.0	0.0	0.0	0.23	2.75

| COLUMN SUMS | 4.59 | 12.16 | 46.33 | 2.06 | 1.61 | 0.69 | 29.82 | 2.75 | 100.00 |

RESULTANT CURRENT IS   0.76 CM/S AT   77 DEG FROM NORTH   TOTAL NO. READINGS   436

MEAN CURRENT IS   1.05 CM/S   PERSISTENCE IS   0.73

MAXIMUM CURRENT IS   5.38 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   16.3 M FROM BOTTOM IN 22.9 M OF WATER

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TABLE 1.08

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50- 22.49	22.50- 67.49	67.50- 112.49	112.50- 157.49	157.50- 202.49	202.50- 247.49	247.50- 292.49	292.50- 337.49	ROW SUMS
1.00 -- 2.99	0.0	0.0	0.0	0.0	14.65	5.72	0.0	0.0	20.37
3.00 -- 4.99	0.0	0.0	0.0	0.08	13.93	5.95	0.02	0.0	19.98
5.00 -- 6.99	0.02	0.02	0.04	0.25	18.24	3.26	0.06	0.04	21.93
7.00 -- 8.99	0.12	0.06	0.08	0.27	7.22	1.95	0.06	0.08	9.85
9.00 -- 10.99	0.04	0.08	0.16	0.21	4.49	1.29	0.27	0.06	6.61
11.00 -- 12.99	0.18	0.04	0.10	0.39	9.56	0.47	0.27	0.08	11.10
13.00 -- 27.99	0.0	0.02	0.0	0.10	9.56	0.37	0.08	0.02	10.16
COLUMN SUMS	0.37	0.23	0.39	1.29	77.66	19.02	0.76	0.29	100.00

RESULTANT CURRENT IS   6.39 CM/S AT 190 DEG FROM NORTH   TOTAL NO. READINGS   4874

MEAN CURRENT IS   6.87 CM/S   PERSISTENCE IS   0.93

MAXIMUM CURRENT IS   27.15 CM/S   READINGS TAKEN EVERY 5 MIN

METER OPERATED AT   4.0 M FROM BOTTOM IN 4.6 M OF WATER

TABLE 1.09

LOCATION CODE : 1150
AREA : HAMILTON HARBOUR
LAKE : ONTARIO

PERIOD : JUL 74
LATITUDE : 43 16 30 N
LONGITUDE : 79 48 24 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50-22.49	22.50-67.49	67.50-112.49	112.50-157.49	157.50-202.49	202.50-247.49	247.50-292.49	292.50-337.49	ROW SUMS
1.00 -- 1.99	0.0	0.0	0.0	0.02	31.09	3.99	0.0	0.0	35.10
2.00 -- 2.99	0.0	0.0	0.0	0.02	6.43	1.52	0.0	0.0	7.97
3.00 -- 3.99	0.0	0.0	0.0	0.0	6.25	0.28	0.0	0.0	6.53
4.00 -- 4.99	0.02	0.0	0.0	0.04	14.34	0.89	0.0	0.0	15.29
5.00 -- 5.99	0.0	0.0	0.06	0.0	3.40	1.03	0.0	0.02	4.51
6.00 -- 6.99	0.0	0.04	0.04	0.08	3.10	0.75	0.0	0.02	4.03
7.00 -- 17.99	0.24	0.24	0.32	0.91	22.35	2.23	0.10	0.20	26.58
COLUMN SUMS	0.26	0.28	0.42	1.07	86.95	10.70	0.10	0.24	100.00

RESULTANT CURRENT IS 4.46 CM/S AT 190 DEG FROM NORTH   TOTAL NO. READINGS 5057

MEAN CURRENT IS 4.69 CM/S   PERSISTENCE IS 0.95

MAXIMUM CURRENT IS 17.50 CM/S   READINGS TAKEN EVERY 5 MIN

METER OPERATED AT 4.0 M FROM BOTTOM IN 4.6 M OF WATER

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TABLE 1.10

LOCATION CODE : 1160   PERIOD   : JUN 74
AREA   : HAMILTON HARBOUR   LATITUDE : 43 17 21 N
LAKE   : ONTARIO   LONGITUDE : 79 47 44 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50- 22.49	22.50- 67.49	67.50- 112.49	112.50- 157.49	157.50- 202.49	202.50- 247.49	247.50- 292.49	292.50- 337.49	ROW SUMS
1.00 -- 1.99	3.42	2.09	3.13	5.83	3.78	2.19	2.43	2.82	25.70
2.00 -- 2.99	1.92	0.88	1.82	8.59	7.86	0.98	0.53	1.23	23.81
3.00 -- 3.99	0.57	0.25	0.70	5.38	6.83	0.23	0.06	0.41	14.42
4.00 -- 4.99	0.06	0.06	0.55	3.66	5.26	0.08	0.04	0.43	10.15
5.00 -- 5.99	0.06	0.0	0.06	3.50	5.69	0.10	0.04	0.02	9.47
6.00 -- 6.99	0.0	0.0	0.0	2.27	3.54	0.04	0.06	0.0	5.91
7.00 -- 12.99	0.0	0.0	0.0	3.17	7.12	0.18	0.06	0.0	10.54
COLUMN SUMS	6.04	3.27	6.26	32.41	40.08	3.81	3.23	4.91	100.00

RESULTANT CURRENT IS   2.89 CM/S AT   159 DEG FROM NORTH   TOTAL NO. READINGS   4888

MEAN CURRENT IS   3.77 CM/S   PERSISTENCE IS   0.77

MAXIMUM CURRENT IS   12.67 CM/S   READINGS TAKEN EVERY 5 MIN

METER OPERATED AT   14.6 M FROM BOTTOM IN 18.3 M OF WATER

TABLE 1.11

LOCATION CODE : 1160   PERIOD   : JUL 74
AREA   : HAMILTON HARBOUR   LATITUDE : 43 17 21 N
LAKE   : ONTARIO   LONGITUDE : 79 47 44 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50-22.49	22.50-67.49	67.50-112.49	112.50-157.49	157.50-202.49	202.50-247.49	247.50-292.49	292.50-337.49	ROW SUMS
0.0 -- 0.30	0.0	0.0	0.0	0.0	0.45	0.0	0.0	0.0	0.45
0.31 -- 0.99	0.0	0.0	0.0	0.02	0.0	0.0	0.0	0.0	0.02
1.00 -- 1.99	2.59	2.16	2.90	3.12	2.95	1.82	1.60	2.00	19.15
2.00 -- 2.99	3.39	2.51	3.99	7.03	8.98	2.13	1.12	2.85	32.00
3.00 -- 3.99	1.57	0.53	1.25	4.91	6.42	0.61	0.22	1.82	17.34
4.00 -- 4.99	1.09	0.10	0.16	3.52	5.87	0.42	0.06	1.63	12.85
5.00 -- 13.99	0.80	0.05	0.10	4.71	10.18	0.50	0.30	1.57	18.20
COLUMN SUMS	9.44	5.35	8.39	23.31	34.85	5.47	3.31	9.88	100.00

RESULTANT CURRENT IS   1.77 CM/S AT 161 DEG FROM NORTH   TOTAL NO. READINGS   6247

MEAN CURRENT IS   3.57 CM/S   PERSISTENCE IS   0.50

MAXIMUM CURRENT IS   13.20 CM/S   READINGS TAKEN EVERY 5 MIN

METER OPERATED AT   14.6 M FROM BOTTOM IN 18.3 M OF WATER

TABLE   1.12

LOCATION CODE : 1180
AREA   : HAMILTON HARBOUR
LAKE   :   ONTARIO

PERIOD   : JUN 74
LATITUDE : 43 16 31 N
LONGITUDE : 7° 47 24 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50-22.49	22.50-67.49	67.50-112.49	112.50-157.49	157.50-202.49	202.50-247.49	247.50-292.49	292.50-337.49	ROW SUMS
0.0 -- 0.30	0.95	2.39	7.60	12.72	19.57	7.07	5.90	3.82	60.03
0.31 -- 0.99	0.43	0.30	0.56	2.60	5.95	0.30	1.30	1.17	12.63
1.00 -- 1.99	0.39	0.0	0.35	2.30	4.25	0.04	0.17	0.65	8.16
2.00 -- 2.99	0.0	0.04	0.17	1.00	3.30	0.09	0.04	0.43	5.08
3.00 -- 3.99	0.0	0.0	0.04	0.95	2.73	0.0	0.0	0.04	3.78
4.00 -- 4.99	0.0	0.0	0.04	1.30	2.65	0.0	0.0	0.09	4.08
5.00 -- 8.99	0.0	0.0	0.0	0.52	5.60	0.0	0.0	0.13	6.25
COLUMN SUMS	1.78	2.73	8.77	21.40	44.05	7.51	7.42	6.34	100.00

RESULTANT CURRENT IS   0.97 CM/S AT 166 DEG FROM NORTH   TOTAL NO. READINGS   2304

MEAN CURRENT IS   1.04 CM/S   PERSISTENCE IS   0.93

MAXIMUM CURRENT IS   8.80 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   5.5 M FROM BOTTOM IN 10.7 M OF WATER

TABLE 1.13

LOCATION CODE : 1180
AREA   : HAMILTON HARBOUR
LAKE   : ONTARIO

PERIOD   : JUL 74
LATITUDE : 43 16 31 N
LONGITUDE : 79 47 24 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50-22.49	22.50-67.49	67.50-112.49	112.50-157.49	157.50-202.49	202.50-247.49	247.50-292.49	292.50-337.49	ROW SUMS
0.0 -- 0.30	2.16	6.87	7.68	7.87	14.13	3.90	2.03	3.00	47.66
0.31 -- 0.99	0.97	0.52	0.65	1.81	7.00	0.42	0.48	1.13	12.97
1.00 -- 1.99	1.16	0.32	0.35	2.26	7.52	0.06	0.06	0.97	12.71
2.00 -- 2.99	0.97	0.10	0.10	1.29	5.36	0.13	0.06	0.45	8.45
3.00 -- 3.99	0.45	0.0	0.0	0.71	5.03	0.0	0.0	0.58	6.78
4.00 -- 4.99	0.19	0.0	0.0	0.39	3.65	0.0	0.0	0.16	4.39
5.00 -- 10.99	0.23	0.0	0.0	0.26	6.55	0.0	0.0	0.0	7.03
COLUMN SUMS	6.13	7.81	8.78	14.59	49.24	4.52	2.65	6.29	100.00

RESULTANT CURRENT IS   1.09 CM/S AT 169 DEG FROM NORTH   TOTAL NO. READINGS   3099

MEAN CURRENT IS   1.39 CM/S   PERSISTENCE IS   0.79

MAXIMUM CURRENT IS   10.55 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   5.5 M FROM BOTTOM IN 10.7 M OF WATER

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TABLE 1.14

LOCATION CODE : 1110
AREA   : BURLINGTON CANAL
LAKE   :   ONTARIO

PERIOD   :   SEP 72
LATITUDE   : 43 17 53 N
LONGITUDE : 79 47 55 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50- 22.49	22.50- 67.49	67.50- 112.49	112.50- 157.49	157.50- 202.49	202.50- 247.49	247.50- 292.49	292.50- 337.49	ROW SUMS
0.0 -- 0.30	0.05	0.0	0.0	0.0	0.0	0.05	0.0	0.05	0.16
0.31 -- 2.99	1.57	2.82	3.31	0.43	0.54	2.01	3.47	0.60	14.75
3.00 -- 5.99	2.44	3.04	7.05	0.11	0.05	2.66	6.40	0.81	22.56
6.00 -- 8.99	2.66	2.28	6.07	0.0	0.16	1.74	5.53	0.54	18.98
9.00 -- 11.99	2.49	1.84	5.26	0.05	0.05	1.03	4.28	0.16	15.18
12.00 -- 14.99	1.84	1.52	3.63	0.0	0.0	0.65	3.85	0.0	11.50
15.00 -- 45.99	2.77	2.66	4.18	0.0	0.0	0.76	6.45	0.05	16.87
COLUMN SUMS	13.83	14.15	29.50	0.60	0.81	8.89	29.99	2.22	100.00

RESULTANT CURRENT IS   2.03 CM/S AT   0 DEG FROM NORTH   TOTAL NO. READINGS   1844

MEAN CURRENT IS   9.38 CM/S   PERSISTENCE IS   0.22

MAXIMUM CURRENT IS   45.08 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   2.1 M FROM BOTTOM IN   9.4 M OF WATER

TABLE 1.15

LOCATION CODE : 1110
AREA   : BURLINGTON CANAL
LAKE   :   ONTARIO

PERIOD   : OCT 72
LATITUDE : 43 17 53 N
LONGITUDE : 79 47 55 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50-22.49	22.50-67.49	67.50-112.49	112.50-157.49	157.50-202.49	202.50-247.49	247.50-292.49	292.50-337.49	ROW SUMS
0.0 -- 0.30	0.02	0.16	0.32	0.04	0.02	0.0	0.18	0.04	0.77
0.31 -- 6.99	0.93	7.02	12.78	0.79	0.77	5.29	12.39	0.81	40.79
7.00 -- 13.99	0.50	3.47	12.73	0.10	0.04	4.32	12.63	0.28	34.05
14.00 -- 20.99	0.30	0.79	4.82	0.02	0.0	1.92	6.44	0.04	14.33
21.00 -- 27.99	0.10	0.24	1.76	0.0	0.0	1.03	2.78	0.0	5.91
28.00 -- 34.99	0.04	0.06	0.54	0.0	0.0	0.30	0.95	0.0	1.88
35.00 -- 122.99	0.0	0.16	0.48	0.0	0.0	0.16	1.47	0.0	2.26
COLUMN SUMS	1.88	11.89	33.42	0.95	0.83	13.02	36.83	1.17	100.00

RESULTANT CURRENT IS   1.74 CM/S AT 262 DEG FROM NORTH   TOTAL NO. READINGS   5045

MEAN CURRENT IS   10.59 CM/S   PERSISTENCE IS   0.16

MAXIMUM CURRENT IS   122.72 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   2.1 M FROM BOTTOM IN   9.4 M OF WATER

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TABLE 1.16

LOCATION CODE : 1110

AREA : BURLINGTON CANAL

LAKE : ONTARIO

PERIOD : NOV 72

LATITUDE : 43 17 53 N

LONGITUDE : 79 47 55 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50-22.49	22.50-67.49	67.50-112.49	112.50-157.49	157.50-202.49	202.50-247.49	247.50-292.49	292.50-337.49	ROW SUMS
0.0 -- 0.30	0.0	0.0	0.58	0.0	0.39	0.0	0.10	0.0	1.07
0.31 -- 2.99	0.0	0.0	0.58	0.0	0.29	0.39	1.74	0.39	3.39
3.00 -- 5.99	0.39	0.78	2.23	0.78	0.87	2.03	4.65	0.39	12.11
6.00 -- 8.99	0.39	0.97	3.59	0.10	0.87	1.36	7.17	0.39	14.83
9.00 -- 11.99	0.39	1.07	5.72	0.10	0.78	0.97	7.95	0.78	17.73
12.00 -- 14.99	0.29	0.48	4.65	0.19	0.19	0.78	6.10	0.29	12.98
15.00 -- 42.99	1.16	1.65	16.38	0.48	0.39	0.87	16.18	0.78	37.89
COLUMN SUMS	2.62	4.94	33.72	1.65	3.78	6.40	43.90	3.00	100.00

RESULTANT CURRENT IS 1.10 CM/S AT 312 DEG FROM NORTH TOTAL NO. READINGS 1032

MEAN CURRENT IS 13.87 CM/S PERSISTENCE IS 0.08

MAXIMUM CURRENT IS 42.59 CM/S READINGS TAKEN EVERY 10 MIN

METER OPERATED AT 2.1 M FROM BOTTOM IN 9.4 M OF WATER

TABLE 1.17

LOCATION CODE : 1110   PERIOD   : MAY 73
AREA   : BURLINGTON CANAL   LATITUDE : 43 17 53 N
LAKE   : ONTARIO   LONGITUDE : 79 47 55 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50–22.49	22.50–67.49	67.50–112.49	112.50–157.49	157.50–202.49	202.50–247.49	247.50–292.49	292.50–337.49	ROW SUMS
0.0 -- 0.30	0.0	0.27	0.07	0.02	0.0	0.0	0.15	0.05	0.57
0.31 -- 7.99	0.40	1.79	0.27	0.07	0.02	0.05	2.09	0.35	5.04
8.00 -- 15.99	0.50	3.08	0.55	0.07	0.15	0.17	2.93	0.74	8.19
16.00 -- 23.99	0.35	3.05	0.60	0.07	0.0	0.10	2.91	0.87	7.95
24.00 -- 31.99	0.27	2.71	0.52	0.07	0.10	0.30	3.82	0.79	8.59
32.00 -- 39.99	0.20	2.88	0.35	0.0	0.02	0.22	3.80	0.37	7.85
40.00 -- 142.99	1.74	25.23	2.78	0.20	0.62	0.94	27.19	3.10	61.81
COLUMN SUMS	3.45	39.01	5.14	0.52	0.92	1.79	42.89	6.28	100.00

RESULTANT CURRENT IS   15.06 CM/S AT 340 DEG FROM NORTH   TOTAL NO. READINGS   4027

MEAN CURRENT IS   55.21 CM/S   PERSISTENCE IS   0.27

MAXIMUM CURRENT IS   142.52 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   6.1 M FROM BOTTOM IN 9.4 M OF WATER

TABLE 1.18

LOCATION CODE : 1110
AREA   : BURLINGTON CANAL
LAKE   :   ONTARIO

PERIOD   :   JUN 73
LATITUDE : 43 17 53 N
LONGITUDE : 79 47 55 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50-22.49	22.50-67.49	67.50-112.49	112.50-157.49	157.50-202.49	202.50-247.49	247.50-292.49	292.50-337.49	ROW SUMS
0.0 -- 0.30	0.03	0.08	0.03	0.0	0.0	0.0	0.0	0.03	0.15
0.31 -- 7.99	0.31	1.77	0.49	0.28	0.23	0.21	0.69	0.33	4.32
8.00 -- 15.99	0.18	2.29	0.69	0.05	0.13	0.26	1.57	0.49	5.66
16.00 -- 23.99	0.39	3.16	0.98	0.13	0.15	0.51	2.03	0.44	7.79
24.00 -- 31.99	0.54	4.01	1.00	0.08	0.26	0.23	2.57	0.28	8.98
32.00 -- 39.99	0.64	4.60	0.95	0.05	0.18	0.26	2.52	0.28	9.49
40.00 -- 143.99	3.94	33.36	4.24	0.72	1.54	1.77	15.69	2.34	63.61
COLUMN SUMS	6.02	49.28	8.38	1.31	2.49	3.24	25.08	4.19	100.00

RESULTANT CURRENT IS   21.73 CM/S AT   39 DEG FROM NORTH   TOTAL NO. READINGS   3888

MEAN CURRENT IS   56.19 CM/S   PERSISTENCE IS   0.39

MAXIMUM CURRENT IS   143.77 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   6.1 M FROM BOTTOM IN   9.4   M   OF WATER

TABLE 1.19

LOCATION CODE : 1110
AREA   : BURLINGTON CANAL
LAKE   :   ONTARIO

PERIOD   : JUL 73
LATITUDE : 43 17 53 N
LONGITUDE : 79 47 55 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50–22.49	22.50–67.49	67.50–112.49	112.50–157.49	157.50–202.49	202.50–247.49	247.50–292.49	292.50–337.49	ROW SUMS
0.0 -- 0.30	0.04	0.02	0.02	0.0	0.0	0.22	0.13	0.07	0.52
0.31 -- 3.99	0.72	2.28	9.16	0.94	0.72	5.09	4.50	0.85	24.26
4.00 -- 7.99	0.38	1.99	14.81	0.52	0.56	3.52	4.68	0.69	27.15
8.00 -- 11.99	0.16	0.92	15.21	0.07	0.16	1.66	2.80	0.13	21.10
12.00 -- 15.99	0.07	0.56	11.38	0.0	0.04	0.69	1.01	0.07	13.82
16.00 -- 19.99	0.0	0.11	6.85	0.0	0.0	0.11	0.58	0.02	7.68
20.00 -- 60.99	0.0	0.20	4.53	0.0	0.0	0.09	0.65	0.0	5.47
COLUMN SUMS	1.37	6.09	61.96	1.52	1.48	11.38	14.36	1.84	100.00

RESULTANT CURRENT IS   5.13 CM/S AT   80 DEG FROM NORTH   TOTAL NO. READINGS   4464

MEAN CURRENT IS   8.85 CM/S   PERSISTENCE IS   0.58

MAXIMUM CURRENT IS   60.08 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   6.1 M FROM BOTTOM IN   9.4 M OF WATER

TABLE 1.20

LOCATION CODE : 1110
AREA   : BURLINGTON CANAL
LAKE   :   ONTARIO

PERIOD   : AUG 73
LATITUDE : 43 17 53 N
LONGITUDE : 79 47 55 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50-22.49	22.50-67.49	67.50-112.49	112.50-157.49	157.50-202.49	202.50-247.49	247.50-292.49	292.50-337.49	ROW SUMS
0.0 -- 0.30	0.06	0.03	0.19	0.13	0.0	0.06	0.35	0.0	0.82
0.31 -- 1.99	0.47	1.20	3.57	0.28	0.54	2.05	2.21	0.60	10.93
2.00 -- 3.99	0.73	1.67	7.77	0.57	0.51	2.53	3.50	0.51	17.78
4.00 -- 5.99	0.41	1.36	8.97	0.38	0.35	1.93	2.97	0.47	16.83
6.00 -- 7.99	0.22	0.95	8.84	0.19	0.16	0.88	2.34	0.19	13.77
8.00 -- 9.99	0.03	0.60	7.04	0.16	0.0	0.41	1.74	0.09	10.07
10.00 -- 31.99	0.06	1.29	25.96	0.13	0.03	0.47	1.80	0.06	29.81
COLUMN SUMS	1.99	7.10	62.33	1.83	1.58	8.34	14.90	1.93	100.00

RESULTANT CURRENT IS   4.89 CM/S AT   77 DEG FROM NORTH   TOTAL NO. READINGS   3167

MEAN CURRENT IS   7.63 CM/S   PERSISTENCE IS   0.64

MAXIMUM CURRENT IS   31.54 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   6.1 M FROM BOTTOM IN   9.4 M OF WATER

TABLE 1.21

LOCATION CODE : 1110
AREA : BURLINGTON CANAL
LAKE : ONTARIO

PERIOD : JUN74
LATITUDE : 43 17 53 N
LONGITUDE : 79 47 55 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50-22.49	22.50-67.49	67.50-112.49	112.50-157.49	157.50-202.49	202.50-247.49	247.50-292.49	292.50-337.49	ROW SUMS
0.0 -- 0.30	0.0	0.69	0.94	0.0	0.16	0.61	0.45	0.0	2.86
0.31 -- 2.99	0.12	4.37	6.82	0.33	0.16	2.78	5.47	0.16	20.22
3.00 -- 5.99	0.41	3.92	10.87	0.94	0.12	2.17	5.68	0.16	24.26
6.00 -- 8.99	0.08	2.41	9.40	0.49	0.04	1.72	4.13	0.0	18.26
9.00 -- 11.99	0.04	0.78	5.80	0.20	0.04	1.23	3.43	0.0	11.52
12.00 -- 14.99	0.0	0.25	5.23	0.12	0.04	0.53	2.17	0.0	8.33
15.00 -- 42.99	0.0	0.61	6.99	0.12	0.04	1.31	5.47	0.0	14.54
COLUMN SUMS	0.65	13.03	46.04	2.21	0.61	10.33	26.80	0.33	100.00

RESULTANT CURRENT IS   1.48 CM/S AT   82 DEG FROM NORTH   TOTAL NO. READINGS   2448

MEAN CURRENT IS   8.13 CM/S   PERSISTENCE IS   0.18

MAXIMUM CURRENT IS   42.90 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   6.1 M FROM BOTTOM IN   9.4 M OF WATER

TABLE 1.22

LOCATION CODE : 1110
AREA   : BURLINGTON CANAL
LAKE   : ONTARIO

PERIOD   : JUL74
LATITUDE : 43 17 53 N
LONGITUDE : 79 47 55 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50-22.49	22.50-67.49	67.50-112.49	112.50-157.49	157.50-202.49	202.50-247.49	247.50-292.49	292.50-337.49	ROW SUMS
0.0 -- 0.30	0.03	0.58	0.64	0.0	0.0	0.23	0.42	0.16	2.06
0.31 -- 2.99	0.26	2.61	5.93	0.23	0.16	1.61	2.42	0.29	13.51
3.00 -- 5.99	0.03	2.80	9.19	0.26	0.16	2.19	2.87	0.13	17.63
6.00 -- 8.99	0.0	2.45	9.64	0.0	0.06	1.23	2.06	0.03	15.47
9.00 -- 11.99	0.16	1.71	11.03	0.0	0.0	0.74	1.16	0.06	14.86
12.00 -- 14.99	0.06	0.90	10.96	0.0	0.0	0.52	0.84	0.03	13.31
15.00 -- 40.99	0.0	1.29	18.25	0.0	0.0	1.32	2.26	0.03	23.15
COLUMN SUMS	0.55	12.35	65.64	0.48	0.39	7.83	12.02	0.74	100.00

RESULTANT CURRENT IS   6.70 CM/S AT   74 DEG FROM NORTH   TOTAL NO. READINGS   3102

MEAN CURRENT IS   10.28 CM/S   PERSISTENCE IS   0.65

MAXIMUM CURRENT IS   40.61 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   6.1 M FROM BOTTOM IN   9.4 M OF WATER

TABLE 1.23

LOCATION CODE : 1110
AREA : BURLINGTON CANAL
LAKE : ONTARIO

PERIOD : AUG 75
LATITUDE : 79 47 55 W
LONGITUDE : 43 17 53 N

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)		337.50- 22.49	22.50- 67.49	67.50- 112.49	112.50- 157.49	157.50- 202.49	202.50- 247.49	247.50- 292.49	292.50- 337.49	ROW SUMS
0.0	-- 0.30	0.54	1.51	0.43	0.15	0.97	0.62	0.35	0.89	5.45
0.31	-- 2.99	0.97	4.52	3.98	1.35	1.85	4.25	4.95	1.62	23.49
3.00	-- 5.99	0.46	5.60	4.68	1.04	0.73	4.02	4.91	0.54	21.99
6.00	-- 8.99	0.19	5.37	3.63	0.31	0.23	3.28	2.90	0.23	16.15
9.00	-- 11.99	0.04	3.86	1.39	0.04	0.0	1.47	2.70	0.08	9.58
12.00	-- 14.99	0.0	2.90	1.08	0.0	0.0	0.77	1.78	0.0	6.53
15.00	-- 44.99	0.08	7.84	1.58	0.08	0.0	1.16	6.07	0.0	16.81
COLUMN SUMS		2.28	31.61	16.77	2.98	3.79	15.57	23.65	3.36	100.00

RESULTANT CURRENT IS   1.02 CM/S AT   41 DEG FROM NORTH   TOTAL NO. READINGS   2588

MEAN CURRENT IS   8.31 CM/S   PERSISTENCE IS   0.12

MAXIMUM CURRENT IS   44.51 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   6.1 M FROM BOTTOM IN   9.4 M OF WATER

TABLE 1.24

LOCATION CODE : 1110
AREA   : BURLINGTON CANAL
LAKE   : ONTARIO

PERIOD   : SEP 75
LATITUDE : 79 47 55 W
LONGITUDE : 43 17 53 N

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50- 22.49	22.50- 67.49	67.50- 112.49	112.50- 157.49	157.50- 202.49	202.50- 247.49	247.50- 292.49	292.50- 337.49	ROW SUMS
0.0 -- 0.30	1.02	6.36	0.97	2.00	2.30	3.13	2.74	0.97	19.49
0.31 -- 2.99	0.97	5.08	1.83	1.53	1.53	2.72	3.62	0.81	18.10
3.00 -- 5.99	0.44	4.06	2.07	1.04	0.63	3.90	2.62	0.49	15.25
6.00 -- 8.99	0.30	3.83	1.44	0.37	0.21	3.13	2.67	0.12	12.07
9.00 -- 11.99	0.02	2.83	1.28	0.09	0.07	1.81	2.76	0.14	9.00
12.00 -- 14.99	0.02	2.37	0.60	0.07	0.02	1.55	2.58	0.0	7.22
15.00 -- 44.99	0.0	4.71	1.49	0.05	0.05	4.57	8.01	0.0	18.87
COLUMN SUMS	2.78	29.24	9.68	5.15	4.80	20.82	24.99	2.53	100.00

RESULTANT CURRENT IS   1.76 CM/S AT 255 DEG FROM NORTH   TOTAL NO. READINGS   4309

MEAN CURRENT IS   7.94 CM/S   PERSISTENCE IS   0.22

MAXIMUM CURRENT IS   44.23 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   6.1 M FROM BOTTOM IN   9.4 M OF WATER

TABLE 1.25

LOCATION CODE : 1114
AREA : BURLINGTON CANAL
LAKE : ONTARIO

PERIOD : AUG 75
LATITUDE : 79 47 55 W
LONGITUDE : 43 17 53 N

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50-22.49	22.50-67.49	67.50-112.49	112.50-157.49	157.50-202.49	202.50-247.49	247.50-292.49	292.50-337.49	ROW SUMS
0.0 -- 0.30	0.04	0.0	0.0	0.12	0.27	0.15	0.58	0.35	1.51
0.31 -- 2.99	0.50	0.15	2.24	1.31	0.69	1.70	2.55	1.04	10.19
3.00 -- 5.99	1.00	0.93	4.09	0.77	0.62	1.43	6.95	1.00	16.79
6.00 -- 8.99	0.42	0.27	4.21	0.27	0.19	0.89	9.57	0.50	16.33
9.00 -- 11.99	0.04	0.19	3.78	0.0	0.04	0.39	9.84	0.42	14.70
12.00 -- 14.99	0.04	0.12	2.35	0.04	0.04	0.19	8.22	0.08	11.08
15.00 -- 46.99	0.0	0.15	5.67	0.0	0.08	0.15	23.35	0.0	29.41
COLUMN SUMS	2.05	1.81	22.35	2.51	1.93	4.90	61.06	3.40	100.00

RESULTANT CURRENT IS   6.17 CM/S AT 260 DEG FROM NORTH   TOTAL NO. READINGS   2591

MEAN CURRENT IS   11.78 CM/S   PERSISTENCE IS   0.52

MAXIMUM CURRENT IS   46.50 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   7.5 M FROM BOTTOM IN   9.4 M OF WATER

TABLE 1.27

LOCATION CODE : 1120
AREA   : BURLINGTON CANAL
LAKE   :   ONTARIO

PERIOD   :   JUN 74
LATITUDE   : 43 17 53 N
LONGITUDE : 79 47 55 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50– 22.49	22.50– 67.49	67.50– 112.49	112.50– 157.49	157.50– 202.49	202.50– 247.49	247.50– 292.49	292.50– 337.49	ROW SUMS
0.0 -- 0.30	0.0	0.74	3.80	0.0	0.20	0.12	0.08	0.08	5.02
0.31 -- 2.99	0.45	3.68	12.62	0.20	0.29	0.78	0.37	0.12	18.50
3.00 -- 5.99	0.53	4.49	14.91	0.08	0.12	1.55	0.49	0.08	22.26
6.00 -- 8.99	0.37	5.47	12.62	0.16	0.04	0.78	0.12	0.0	19.57
9.00 -- 11.99	0.04	4.53	8.46	0.0	0.0	0.74	0.16	0.0	13.93
12.00 -- 14.99	0.0	3.31	5.43	0.0	0.0	0.16	0.04	0.0	8.95
15.00 -- 39.99	0.0	5.68	5.35	0.0	0.0	0.53	0.20	0.0	11.76
COLUMN SUMS	1.39	27.90	63.19	0.45	0.65	4.66	1.47	0.29	100.00

RESULTANT CURRENT IS   6.66 CM/S AT   66 DEG FROM NORTH   TOTAL NO. READINGS   2448

MEAN CURRENT IS   7.80 CM/S   PERSISTENCE IS   0.85

MAXIMUM CURRENT IS   39.75 CM/S   READINGS TAKEN EVERY 10 MIN

METER OPERATED AT   2.1 M FROM BOTTOM IN   9.4 M OF WATER

TABLE 1.28

LOCATION CODE : 1120   PERIOD   : JUL 74
AREA   : BURLINGTON CANAL   LATITUDE : 43 17 53 N
LAKE   : ONTARIO   LONGITUDE : 79 47 55 W

FREQUENCY TABLE

DIRECTION (COMING FROM) IN DEGREES

SPEED(CM/S)	337.50- 22.49	22.50- 67.49	67.50- 112.49	112.50- 157.49	157.50- 202.49	202.50- 247.49	247.50- 292.49	292.50- 337.49	ROW SUMS
0.0 -- 0.30	0.0	1.29	0.0	0.0	0.10	0.26	0.26	0.0	1.90
0.31 -- 2.99	0.39	5.25	0.13	0.06	0.26	1.22	0.39	0.10	7.80
3.00 -- 5.99	0.64	8.25	0.13	0.0	0.23	2.38	0.23	0.16	12.02
6.00 -- 8.99	0.29	10.96	0.0	0.03	0.03	1.26	0.10	0.0	12.67
9.00 -- 11.99	0.10	13.63	0.03	0.03	0.13	1.06	0.06	0.0	15.05
12.00 -- 14.99	0.06	14.76	0.0	0.0	0.0	0.35	0.0	0.0	15.18
15.00 -- 41.99	0.03	33.74	0.03	0.0	0.06	1.51	0.0	0.0	35.39
COLUMN SUMS	1.51	87.88	0.32	0.13	0.81	8.06	1.03	0.26	100.00

RESULTANT CURRENT IS   10.85 CM/S AT   33 DEG FROM NORTH   TOTAL NO. READINGS   3103

MEAN CURRENT IS   12.54 CM/S   PERSISTENCE IS   0.87

MAXIMUM CURRENT IS   41.25 CM/S   READINGS TAKEN EVERY 10 MIN

                METER OPERATED AT   2.1 M FROM BOTTOM IN   9.4 M OF WATER

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HAMILTON HARBOUR STUDY 1976

SECTION H

RATES OF OXYGEN UTILIZATION IN THE HYPOLIMNION

RATES OF OXYGEN UTILIZATION IN THE HYPOLIMNION OF HAMILTON HARBOR, 1976

SUMMARY

THE OBJECTIVE OF THIS WORK WAS TO DETERMINE THE RATE OF OXYGEN UTILIZATION IN THE HYPOLIMNION AND ITS RELATIONSHIP TO METHANE OXIDATION IN THE WATER COLUMN. OCEANOGRAPHIC TECHNIQUES WERE USED TO MEASURE SMALL CHANGES IN OXYGEN CONCENTRATION; RADIOACTIVE METHANE WAS USED AS A TRACER TO MEASURE METHANE OXIDATION. THE AVERAGE VOLUMETRIC RATE OF OXYGEN CONSUMPTION WAS 1.0 MG/L-DAY FOR AREAS REPRESENTATIVE OF THE HYPOLIMNION FOR THE PERIOD JULY 1- AUG. 15, 1976. METHANE OXIDATION RATES WERE GENERALLY AN ORDER OF MAGNITUDE LOWER, DUE TO LOW METHANE CONCENTRATIONS. SEDIMENT OXYGEN DEMAND WAS ESTIMATED TO BE OF THE ORDER OF 2 GM/M^2-DAY. THESE DATA SUGGEST THAT WATER COLUMN PROCESSES, RATHER THAN SEDIMENT OXYGEN DEMAND, DOMINATE THE RATE OF HYPOLIMNETIC OXYGEN DEPLETION.

HAMILTON HARBOR STUDY

RATES OF OXYGEN UTILIZATION IN THE HYPOLIMNION OF
HAMILTON HARBOR, 1976

Rapid loss of hypolimnetic oxygen after the onset of spring
stratification has been observed in Hamilton Harbor (MOE,
1974, 1975, 1977). It is useful to divide the mechanisms
of oxygen demand into two major categories. (1) water column
demand due to such bacterial processes as oxic decomposition
of organic matter and oxidation of methane, (2) sediment
oxygen demand. The first represents processes occurring
throughout the water column, the later is an interfacial
process occurring at the sediment-water zone of contact.

The objective of this chapter is to determine the magnitude
of oxygen demand due to water column processes and to
compare this demand to other mechanisms of oxygen demand.

Methods

The rate of oxygen depletion due to water column processes
was determined using methods similar to the dark bottle
portion of the light-dark method for measuring primary
production. A sample is obtained from a given depth by a
Van Dorn sampler and then conducted directly into a 125 mℓ
black bottle without any contact with air, overflowing the
bottle 2-3 times. This minimizes disturbance of bacterial
processes and prevents change in oxygen concentration in
the sample. The bottle is blackened to prevent entrance
of any sunlight into the bottle. A minimum of two bottles
are taken at one depth. One is spiked (see next para-
graph for definition of 'spike') at time zero to stop
oxygen utilization, the other may be returned to depth in the
water column and retrieved later or taken into the laboratory
and incubated at the in situ temperature. After a predetermined
time period, this second bottle is likewise spiked.

The oxygen concentration is measured using the micro-
titrator method of Strickland and Parsons (1968). One mℓ
of an alkali-azide solution and one mℓ of a manganous sulfate
solution is added to the 125 mℓ bottle, reacting with oxygen
to form a precipitate (this is the so called spike). This
spike causes all bacterial action to cease. One mℓ of
sulfuric acid is added to react and liberate iodine; 50 mℓ
of sample is then titrated with 0.01-0.025N sodium thio-
sulfate. Starch indicator is added when the iodine solution is
a straw yellow. The titrant is added using a micro-titrator
which is capable of adding 0.001 mℓ of titrant in a drop. This
method is similar to the standard Winkler method for measuring
dissolved oxygen (WPCF, 1975) except smaller quantities of
sample and more dilute solutions of titrant are used,

and a much more exact method of measuring the quantity of
titrant is used.

Charlton (personal communication) has successfully applied
this method to measuring oxygen depletion rates in Lake
Ontario. Samples are taken at depth, two bottles are spiked
at time zero and two bottles are resuspended at depth for
two to four hours from a ship. The samples are retrieved,
spiked and then titrated. Our field techniques are somewhat
different as we desired to obtain kinetic information.
Secondly, four bottles (similar to Charlton) are filled with
one sample in the field, but not spiked. All bottles are
brought into the laboratory and incubated. Then at various
times, one bottle is removed and spiked. Generally, the
bottles were removed at time 0, 3, 6 and 13 hours, spiked
and titrated within 12 hours. No detectable differences
were observed in oxygen concentration of spiked samples
titrated within 2 days of the time of spiking.

Three major sources of error exist in determining these
rates of oxygen depletion. During the initial sampling,
care must be taken to overflow the bottle and to prevent
entrapment of air. While titrating, it is difficult to
exactly detect the end-point when small volumes of titrant
are added as the change from blue to clear goes through a
grey colour; much practice is required before consistency
is obtained. Further, due to the precision desired,
significant changes in the thiosulfate concentration occurs
between morning and afternoon; accordingly the titrant must
be standardized every few hours. The third major error
relates to the question of surface area in the bottle. If
few bacteria and small quantities of surface area are
present in the sample, the extra surface area of the bottle
walls can provide a site to which bacteria could attach and
possibly affect the rates of oxygen depletion. If the
surface area of the particles in the sample is much greater
than that of the bottle walls or if the time of measurement is
shorter than two to three times that of the time of cell
division, the effect of bottle walls is insignificant. Our
calculations suggest that the surface area of the particles is
much greater than that of the bottle walls and hence this error
is insignificant.

Our major source of error lies in inadequate care in
transferring the sample from the Van Dorn into the bottle.
If two samples each are titrated from replicate bottles,
differences may exist between bottles, but generally the same
concentration was measured in the two samples from the same
bottle. This indicates that endpoint detection was consistent,
but that errors in filling the bottles are the most
significant source of error.

The rate of methane oxidation was measured, using radio-active

methane ($C^{14}H_4$) and the method of Rudd et al (1974),
Rudd and Hamilton (1975). The methane concentration
was measured using a Hewlett-Packard gas chromatograph
outfitted with a flame ionization detector.

Results

The measured rates of oxygen consumption are shown in Table 1.
All samples were incubated at 15°C-16°C, a temperature
representative of the hypolimnetic areas for the July-August
period. The hypolimnetic rates (7m and deeper) range from
0.20 to 2.3 mg/ℓ-day, averaging 1.0 mg/ℓ-day. Typical rate
data upon which the data of Table 1 are based are shown
in Figure 1 and 2 for July 15 and July 21. These graphs are
linear with the odd point being off the line. Such a non-
conforming point is probably due to problems with filling
the sample bottle.

The rates of oxygen consumption are quite variable, showing
no consistent trend as a function of depth or of oxygen
concentration (see Table 1 - the time constant, assuming zero
order kinetics, shows no general relationship with oxygen
concentration). This temporal and physical variability is
also present in other chemical and physical characteristics
of the Harbor and is doubtless caused by similar mechanisms,
probably variable physical transport processes.

The nature of the functional relationship between oxygen con-
consumption rate and oxygen concentration requires further
attention. Figures 1 and 2 suggest that the rate is independent
of oxygen concentration, indicating that zero order kinetics
are appropriate. This is undoubtedly due to the narrow range
of oxygen change for each depth - such small changes   do not
permit adequate assessment of the kinetics for the full range
of oxygen concentrations from 0 to 8 mg/ℓ. For two different
twenty-four hour runs in which 2 bottles were removed at each
time (see Figure 3), the rate of oxygen depletion is approx-
imately linear with time. Some unexplainable variations (e.g.,
June 14, 17m, station 258 of Figure 3b), in which a succeeding
concentration is higher than a preceeding concentration, are
observed. Such unexplainable variations have also been ob-
served by Charlton (personal communication). Examination of
data on Table one indicates that there is a weak correlation
between oxygen consumption rate and oxygen concentration
(r^2=0.18, n = 44; such a correlation implies first order
kinetics - the rate of oxygen consumption varies as the oxygen
concentration to the power of one). Thus in general, oxygen
kinetics appear to be zero order for small changes in oxygen
concentration, but whether oxygen kinetics are non-zero order
over the full range of possible oxygen concentrations requires
further assessment.

Dissolved methane concentrations are shown in Table 2
Analyses were not conducted weekly due to gas chromatograph
problems. Insignificant concentrations of methane were
generally observed throughout the water column, except
directly adjacent to the sediments. The rates of methane
oxidation are shown in Table 3. The rate constant for
conversion of methane to carbon dioxide decreased during July;
the rate of oxygen consumption due to methane oxidation is
an order of magnitude smaller than the rate of oxygen
utilization by water column processes. If the rate constant
during other periods is higher, as in early July, the methane
oxidation rate would be higher but lower than the rate of
water column consumption. Accordingly methane oxidation
appears to be an insignificant portion of water column
oxygen consumption.

Rates of sediment oxygen demand were measured at Stations
270, 258 and #4 and are shown in Table 4. (Walker and
Snodgrass, 1978). These rates are similar to those
reported by Polak and Haffner (1978). Overall, the sediment
oxygen demand is of the order of 2 g oxygen/m^2-day. For
an average depth of the hypolimnion of 8m, the volumetric
rate of oxygen consumption due to water column processes is
8 g oxygen/m^2-day. Accordingly, water column processes
appear to have a much greater effect than sediment processes
upon the hypolimnetic oxygen budget.

From observations on the disappearance of standing stocks of
oxygen from the Harbor during the spring time (MOE, 1975, 1977),
the rate of disappearance is approximately 1 gm/m^2-day. During
summer stratification, the hypolimnetic oxygen concentration
remains approximately constant. To maintain these conditions,
a large source of oxygen is required. Large amounts of
oxygen must be transported across the thermocline and/or
from Lake Ontario in the hypolimnion in order the hypolimnion
maintain the minimum amount of oxygen that is present, since
the net rate of decrease hipolimnetic oxygen (in the spring)
is much smaller (MOE, 1975).

Conclusions

In 1976, water column processes were the dominant mechanism
for utilization of hypolimnetic oxygen; sediment processes
were a small sink for oxygen, representing approximately
20% of the total.

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TABLE 1

Volumetric Rates of Oxygen Consumption

1976

Date 1976	Station No.	Depth (m)	Volumetric Rate of Oxygen Consumption (mg/ℓ-day)	Initial Oxygen Concentration (mg/ℓ)	Time Constant (h^{-1})
July 9	258	7	0.960	5.002	0.0080
		10	0.929	4.533	0.0085
		13	0.480	4.181	0.0048
		16	0.259	3.962	0.0027
		19	0.960	3.779	0.0106
July 13	258	7	0.487	4.314	0.0047
		10	0.192	4.045	0.0020
		13	0.280	3.941	0.0030
		19	0.204	2.902	0.0029
July 15	258	7	1.03	4.277	0.0101
		10	1.08	4.158	0.0108
		13	0.235	3.427	0.0029
		16	0.271	3.264	0.0035
		19	0.156	3.056	0.0021
July 21	258	5	1.54	8.003	0.0080
		10	0.386	6.182	0.0026
		13	1.26	5.590	0.0091
		16	1.37	4.493	0.0127
		19	1.20	3.649	0.0137
July 28	258	1	3.92	7.672	0.0213
		5	2.95	5.621	0.0219
		13	2.27	3.779	0.0250
Aug. 3	4	5	1.03	6.666	0.0065
		7	0.886	5.688	0.0065
		10	1.33	4.776	0.0116
		13	1.33	3.765	0.0147
		16	0.991	2.643	0.0156
		19	0.986	1.899	0.0216
Aug. 9	258	5	1.66	7.051	0.0098
		7	1.48	5.963	0.0105
		10	1.24	4.734	0.0109
		13	1.63	3.829	0.0177
		16	1.34	2.618	0.0213
		19	1.61	1.059	0.0404

TABLE 1 cont'd

Date 1976	Station No.	Depth (m)	Volumetric Rate of Oxygen Consumption (mg/ℓ-day)	Initial Oxygen Concentration (mg/ℓ)	Time Constant (h^{-1})
Aug. 11	270	1	4.00	6.749	0.0247
		3	2.18	5.366	0.0170
		5	2.04	4.402	0.0193
		7	1.59	3.396	0.0195
		9	1.29	2.513	0.0213
		11	1.39	1.699	0.0341
		13	1.39	0.917	0.0633
Aug. 11	252	1	1.09	6.774	0.0067
		3	1.04	6.207	0.0070
		5	1.25	5.619	0.0093

TABLE 2

Dissolved Methane Concentrations

1976

Date/Station

Depth	July 21 Stn 258	July 28 Stn 258	Aug. 3 Stn 4	Aug. 18 Stn 252	Aug. 18 Stn 270	Aug. 18 Stn 4	Aug. 18 Stn 258
1	0	.15µM	0µM	.75µM		0.64µM	0µM
2							
3	0		.15	.94			
4						0	0
5	0	.15	0		0µM		
6				1.8µM			
7	0		0		0	0	0
8							
9							
10	.31µM		0		0	0	0
11	.31						
12	.15						
13	.15	.15	0		3.05	0	0
14	.31						
15	.15					0	0
16	.15		0			4.58	0
17	.15						
18	.23					8.98	0
19	.15		.15			14.3	9.35
20	.15						

Note: all zero values are <0.15µm, as this is the detection limit

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TABLE 3

Rates of Methane Oxidation

Date Station	Depth (m)	Methane Oxidation Constant (CH_4 to CO_2; h^{-1})	Methane Oxidation Rate (mgO_2/ℓ-day)	Water Column Oxygen Rate (mgO_2/ℓ-day)
June 22	8	0.136	--	--
#(258)	13	0.102	--	--
July 7	1	0.116	--	--
#(258)	4	0.061	--	--
	7	0.153	--	--
	10	0.168	--	--
	13	0.181	--	--
	16	0.210	--	--
	19	0.210	--	--
July 21	1	0.015	0	--
#(258)	5	0.104	0	1.538
	7	0.016	0	--
	10	0.044	0.0206	0.386
	13	0.017	0.0041	1.226
	16	0.031	0.0073	1.370
	19	0.057	0.0014	1.200
July 28	1	0.0018	0.004	3.924
#(258)	5	0.014	0.0033	2.954
	13	0.010	0.0025	2.270
Aug. 3	1	0.0011	0	--
# (4)	3	0.0098	0.002	--
	5	0.0062	0	1.034
	7	0.0082	0	0.886
	10	0.0542	0	1.329
	13	0.0446	0	1.327
	16	--	--	0.991
	19	0.1685	0.0362	0.986

* Methane Oxidation Rate of zero means that no rate was detected as the dissolved methane concentration was below the detection limit.

TABLE 4

In Situ Measurements of Total
and Chemical SOD (g /m^2-day)

Station	In Situ Measurement	Form of SOD
270	2.21	Total
270	1.30	Total
270	1.82	Total
270	0.30	CSOD
258	2.03	Total
258	1.27	Total
258	1.14	Total
258	0.30	CSOD
4	2.02	Total
4	1.90	Total
4	0.36	CSOD
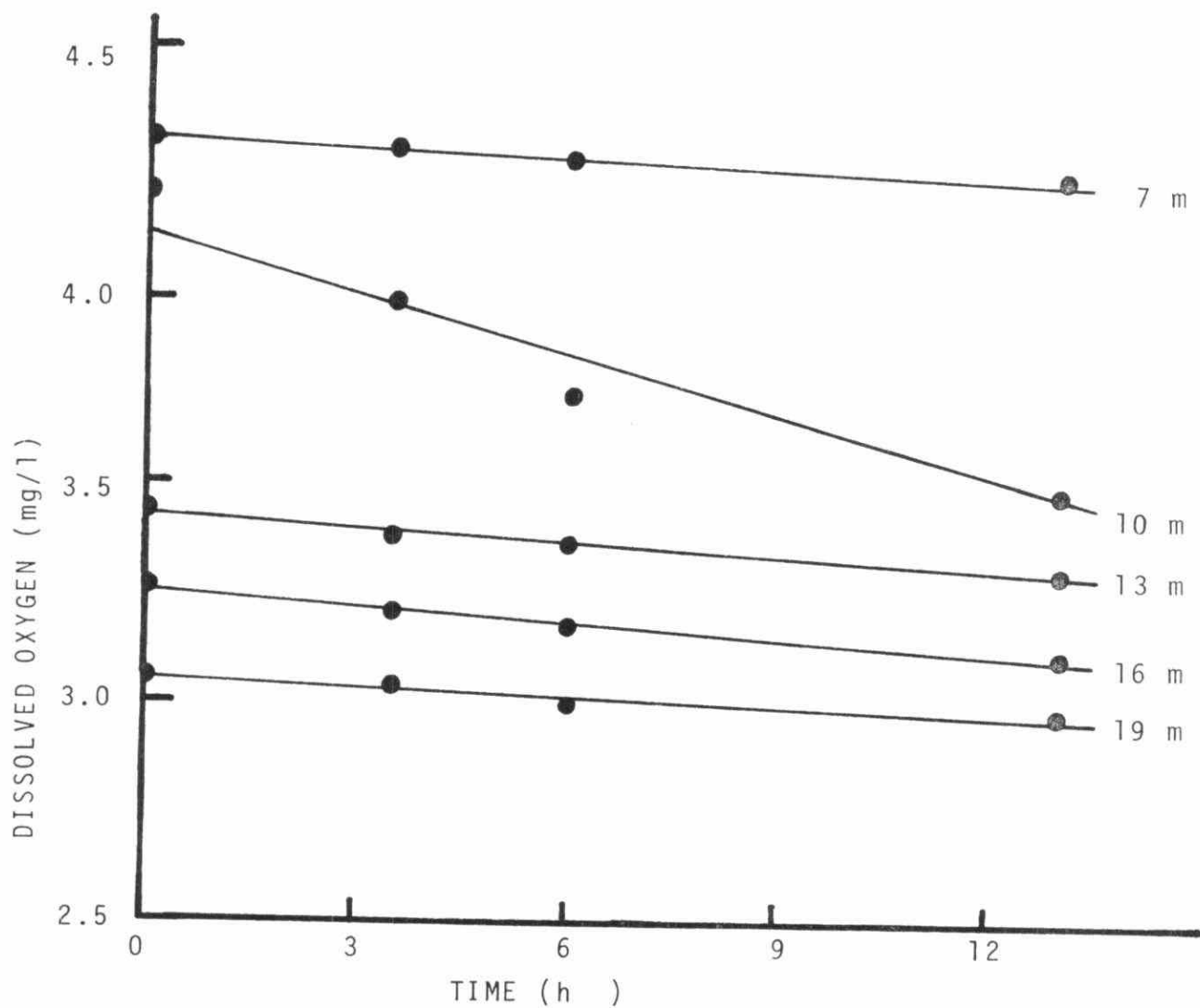
FIGURE 1. RATE OF DISSOLVED OXYGEN DEPLETION AT
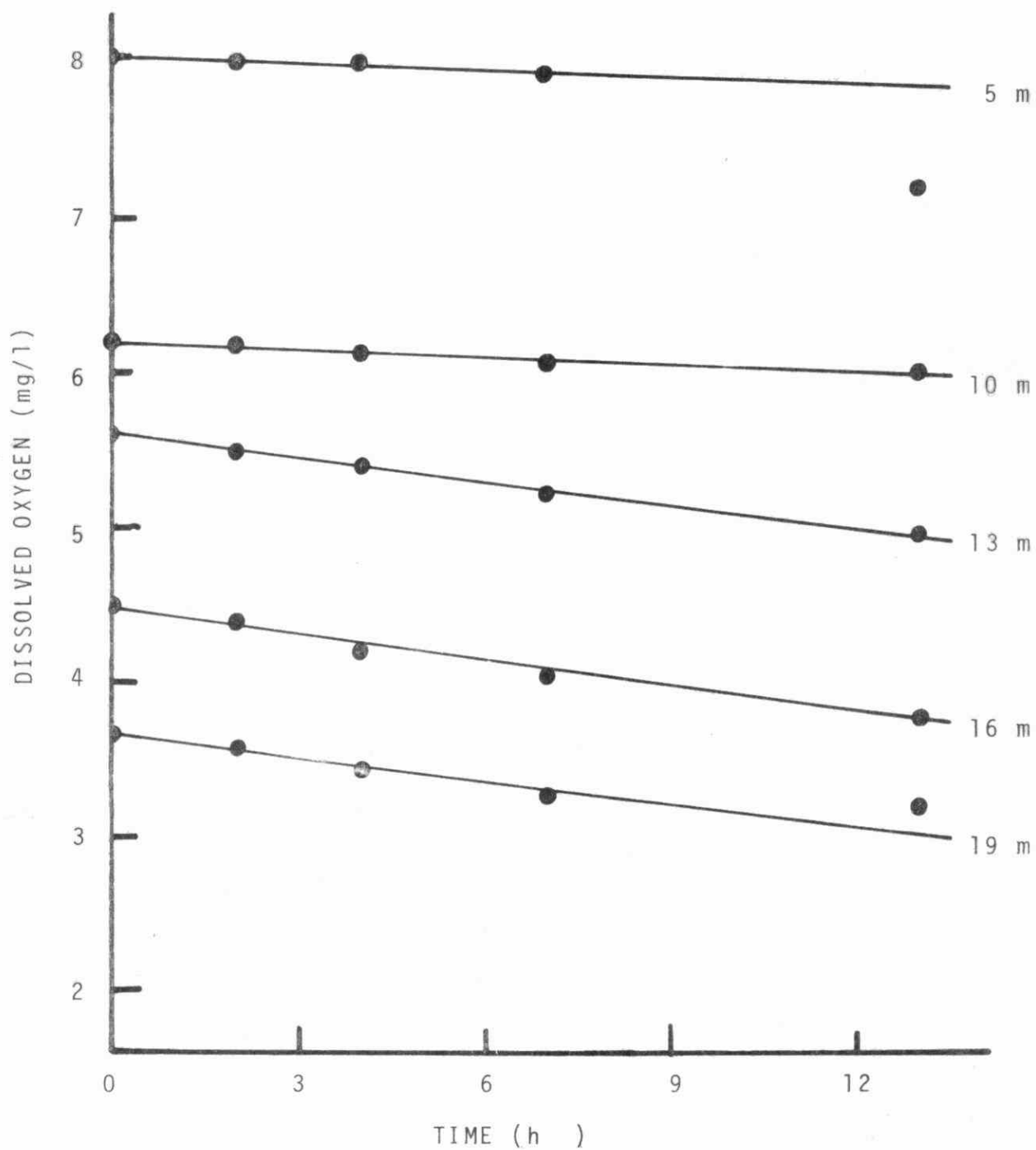DIFFERENT DEPTHS OF STATION 258, JULY 15,1976.

FIGURE 2. RATE OF DISSOLVED OXYGEN DEPLETION AT
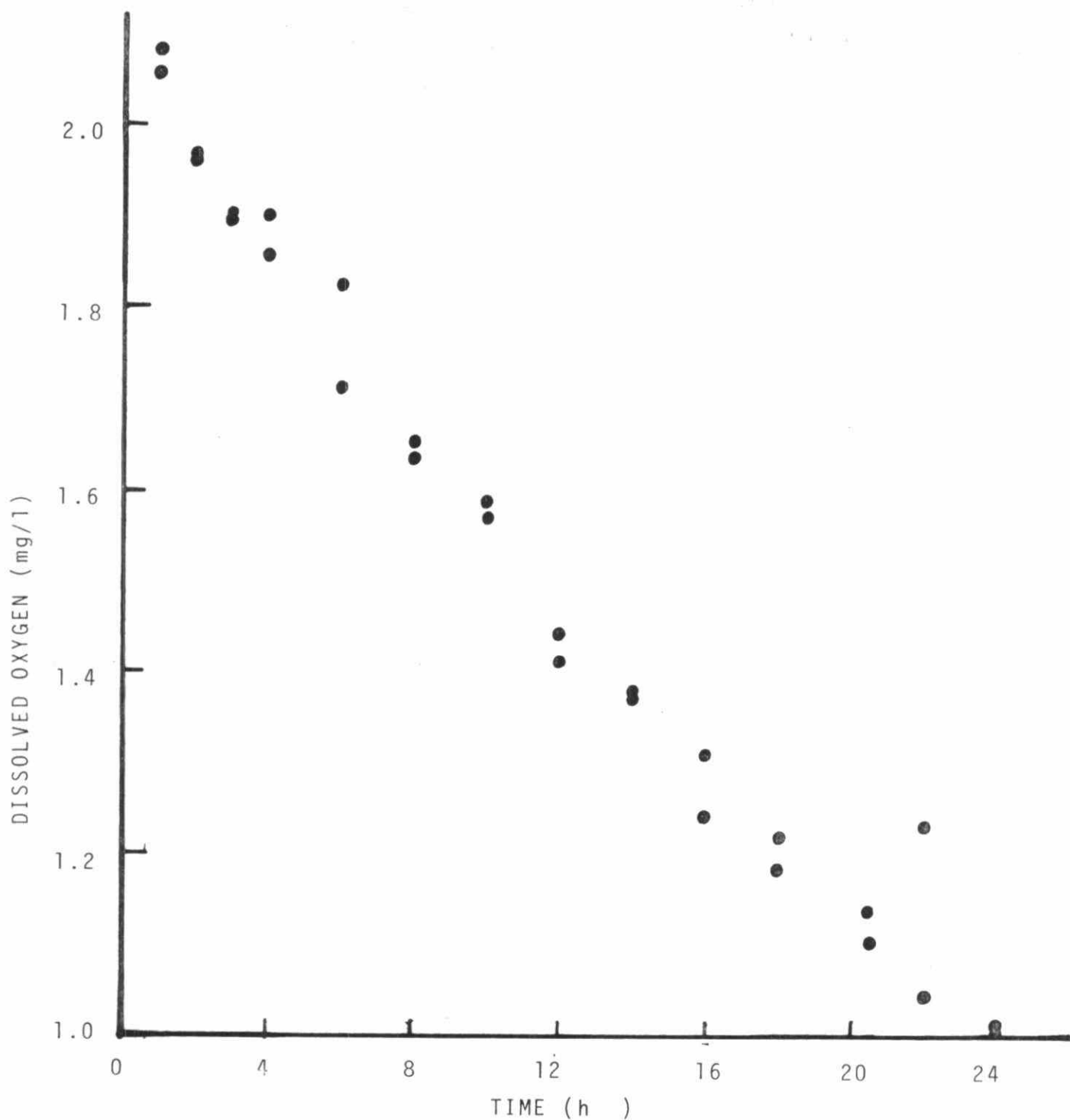
DIFFERENT DEPTHS OF STATION 258, JULY 21,1976

FIGURE 3a.   KINETICS OF DISSOLVED OXYGEN DEPLETION (Sample

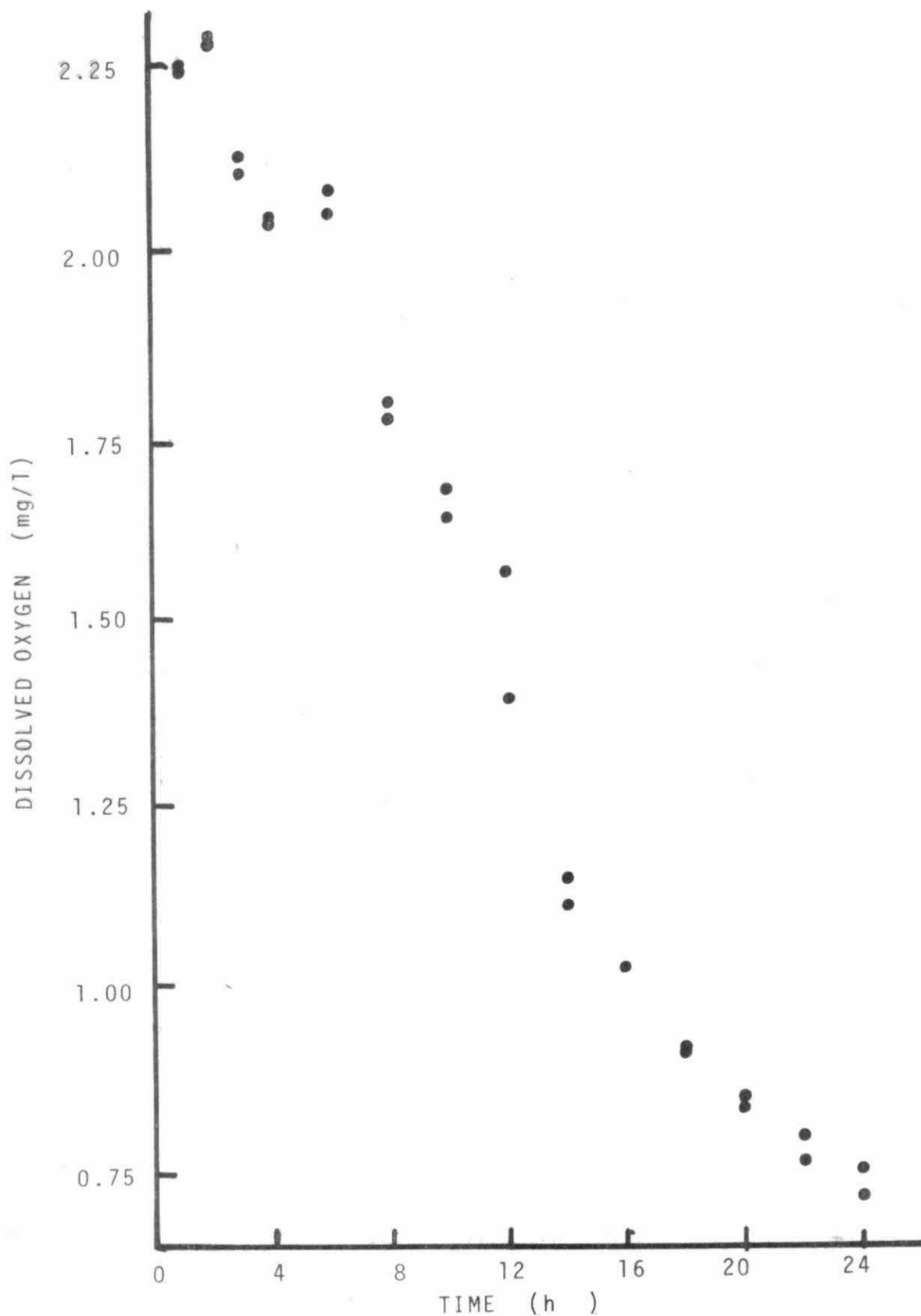from 13 m, June 14,1976, Station 258,12 °C).

FIGURE 3b. KINETICS OF DISSOLVED OXYGEN DEPLETION
(Sample from 17 m, June 14, 1976, Station 258, 12°C).

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